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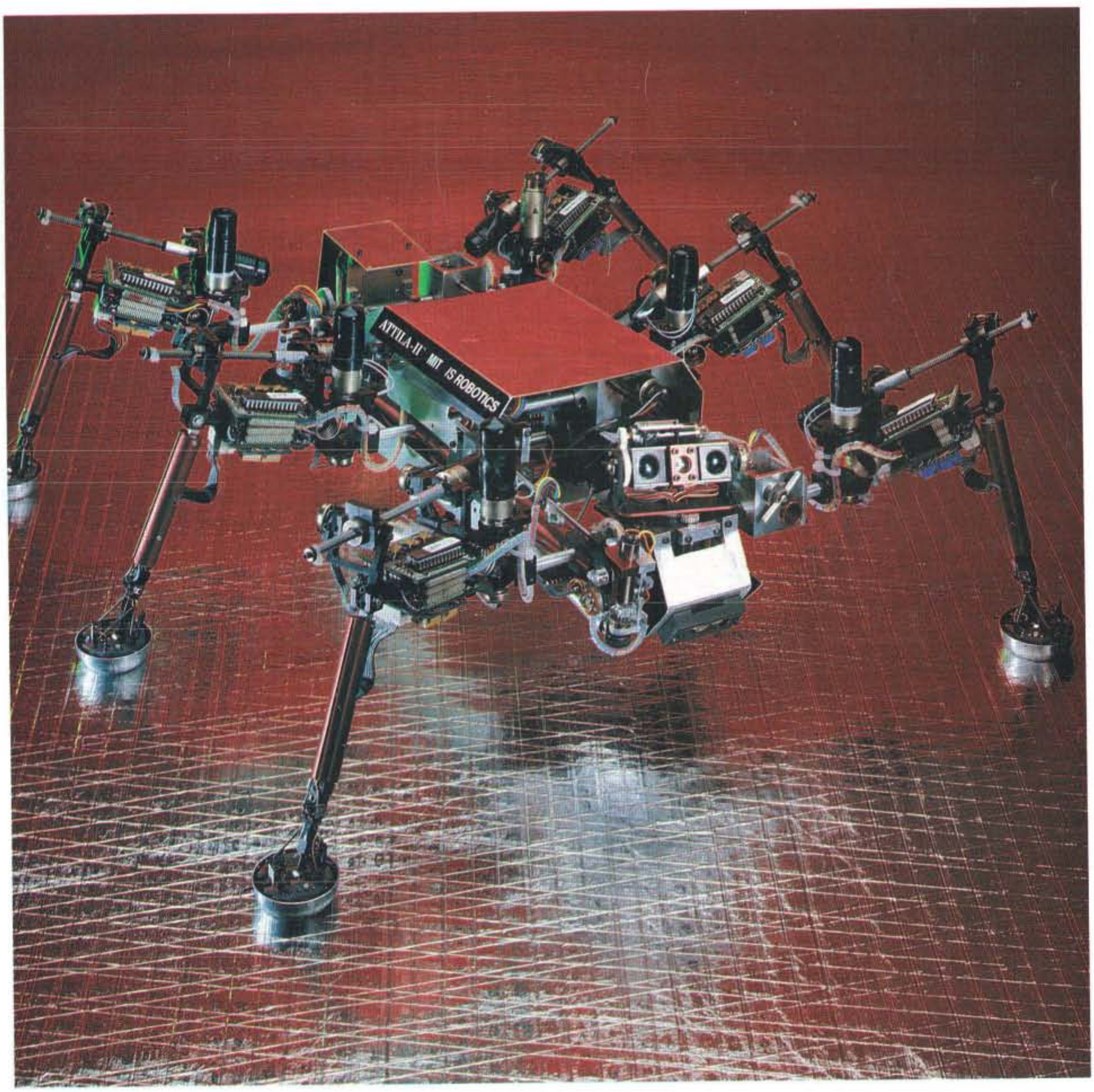

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SCIENTIFIC AMERICAN

December 1991 Volume 265 Number 6

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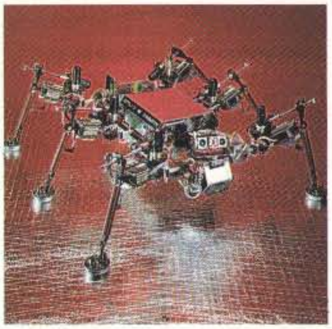
DEPARTMENTS



THE COVER photograph shows an insect-like, reflex-driven robot under development at the Massachusetts Institute of Technology. The current models, named Attila and Hannibal, explore the M.I.T. Artificial Intelligence Laboratory; future versions might be deployed to gather information on other planets. Although the M.I.T. robots operate almost entirely by reflex, artificial intelligencers are locked in intense debate over the amount of reasoning and knowledge such machines will require (see "Silicon Babies," by Paul Wallich, page 82).

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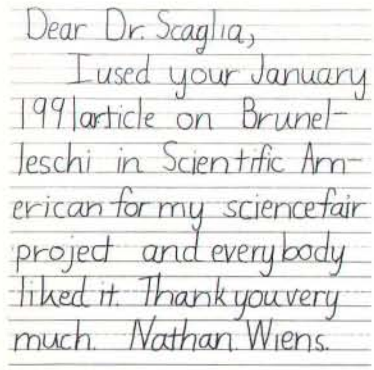
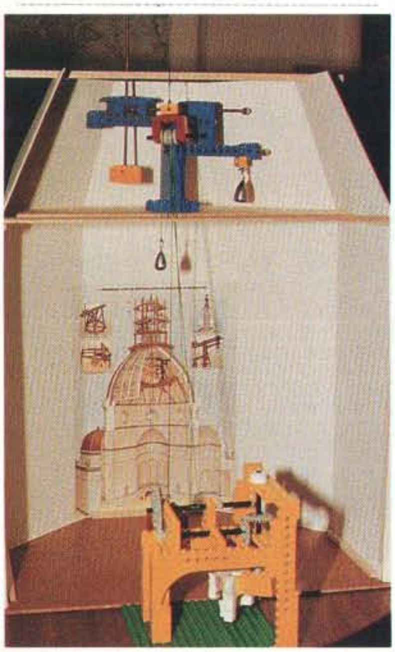
LETTERS TO THE EDITORS

The Next Generation


Dear Dr. Scaglia,
I used your January 1991 article on Brunelleschi in Scientific American for my science fair project and everybody liked it. Thank you very much. Nathan Wiens.



Good Nukes, Bad Nukes

It is unfortunate that *Scientific American* chose to print "Nuclear Power in Space," by Steven Aftergood, David W. Hafemeister, Oleg F. Prilutsky, Joel R. Primack and Stanislav N. Rodionov [June], as an objective consideration of the technical and safety concerns over nuclear-powered satellites. The article presents as meaningful facts mere fragments of data that cannot be put in perspective by most readers.

The opening paragraph refers to the "extensive history of accidents and failures" and to "numerous" releases of radioactivity. The authors then proceed to describe the three releases of nuclear material to the upper atmosphere that have occurred. Do three events truly merit the description "numerous"?

The release of "17,000 curies of plutonium 238" following the failure of the *Transit 5BN-3* navigational satellite to achieve orbit is presented without any means for considering its significance. The amount of radium 226 alone naturally present in the earth's surface dwarfs by orders of magnitude the "environmental burden" of plutonium added by man.

The claim that nuclear power sources for satellites create international tension confuses cause and effect. It is not the power source that causes tension but rather the operation of the military reconnaissance and navigational satellites. Tension and conflicts aside, those satellites have contributed to the remarkably enduring (albeit uneasy) truce between the superpowers for the past five decades.

The apparent support given to the use of nuclear power for distant space purposes is also misleading. These uses, such as the plutonium power sources on the *Galileo* and *Ulysses* space probes, have been opposed by activist groups, using the same strategies and arguments as those of the authors.

R. J. TUTTLE
Moorpark, Calif.

Aftergood, Hafemeister and Primack respond:

Of the roughly 65 space missions that used a nuclear power supply, at least 10 were terminated by an accident, a launch abort or some other failure. At least five resulted in the release of radioactivity into the biosphere.

It is hard to see how Soviet surveillance satellites powered by nuclear reactors have contributed to the "truce" between the superpowers. Rather the *RORSAT* program, suspended in 1988, threatened to stimulate the development of antisatellite weapons by the U.S. Military applications of space nuclear power may begin as only the manifestations of conflict, but they soon form a causal link in arms competition; they are well worth controlling.

Our support of nuclear power for deep space uses is genuine—and it has been effective. A Federation of American Scientists report on nuclear safety aspects of the Galileo mission was cited by the National Aeronautics and Space Administration to help persuade a federal judge to allow that spacecraft to be launched.

What Is a Weed?

The unexamined assumptions underlying "Biological Control of Weeds," by Gary A. Strobel [SCIENTIFIC AMERICAN, July], are deeply troubling. Strobel champions an industry aimed at eradicating not a clearly defined target, like AIDS or cancer, but a family of plants chosen by the most superficial human subjectivity. We simply have no idea what essential functions these plants perform. Many of them may defy laboratory elucidation because they are entirely passive or catalytic, in the same way that a coral reef provides shelter for myriad marine species.

His approach also conceals a second, more disturbing level of trivializing subjectivity: Strobel and his like-minded colleagues devote careers to making commercially valuable plants thrive and making plants without recognized uses vanish. They merrily champion the extinction of plants that could possibly save our lives.

ROBERT B. MERKIN
Northampton, Mass.

Strobel responds:

Weeds are basically "plants out of place." In its home environment, a plant may be controlled by pathogens, insects or other competing plants. Once carried to a new location where it faces no competitors, however, the same plant may threaten wildlife, the landscape, livestock and people by proliferating dramatically.

People who practice and study biological control do not represent a cult bent on annihilating weedy plants. Quite the contrary, biological control measures usually suppress the invading weed population without eliminating it by increasing the number of its competitors. Because biological control measures are generally not directed at a weed population's native point of origin, no potentially valuable germ plasm is destroyed. There is not a single documented case of the loss of a plant through the practice of biological control.

50 AND 100 YEARS AGO

DECEMBER 1941

"Newspaper reports from London reveal what has been suspected for some time: the British are using catapult-launched single-seater fighters on board freighters as protection against air attack, employing small Hurricanes of relatively short range but with sufficient fire power successfully to attack a four-engined Focke-Wulf bomber. The pilots are specially trained and particularly courageous men. They need both qualities because the service is such a hazardous one. Suppose the pilot shoots off via the catapult and downs the enemy in the air, or the submarine by means of a depth charge. He cannot land on the deck of the freighter, so he has but two alternatives: To seek a land airport, hoping that his fuel supply will be sufficient, or else to 'mush' into the water as near a ship as possible."

"During World War I this nation was faced with an industrial problem similar to the one that now pertains. There were no facilities for training skilled mechanics in the numbers needed. To remedy this the Smith-Hughes Act was passed, providing for federal appropriations for the creation and operation of trade schools. For awhile things progressed favorably, but soon after World War I the snobbery of academic education gained the upper hand. By legal means it was decreed, in most of the industrial states, that no one could teach in secondary schools unless he or she had graduated from an accredited university. Death came to the trade schools. Since 1925 no highly skilled trades have been taught in the public schools."

"Spraying sulfadiazine, one of the new miracle sulfa drugs, directly on burns is being hailed as the most effective method of treating burns yet devised. At the Johns Hopkins Hospital, in Baltimore, 114 badly burned patients were swiftly healed by the new method. Burned areas 'healed more rapidly than with any form of treatment previously used at the Johns Hopkins Hospital,' surgeons on the hospital staff declare. Some of them believe the sulfadiazine method will eliminate the need for skin grafting and plastic surgery to efface scars and correct deformities."

SCIENTIFIC AMERICAN

DECEMBER 1891

"M. de Chauveau had the idea of exporting water from the Dead Sea as an antiseptic for use in hospitals, it being reputed mortal to every kind of animal life, and necessarily, as he supposed, to microbes. But a savant whom he consulted said, 'Take care, there is hardly a fluid in nature in which a virulent microbe of some sort may not find a good soil.' He therefore cultivated various kinds of bacilli in the densest Dead Sea water that had ever been fetched to his laboratory. The diphtheria, measles, scarlatina, small pox, and other fell creatures of the animalcular world were experimented upon. All died but two, with which in forty-eight hours the fluid was alive. The one shaped like the clapper of a bell and the other like a tack nail with a round head were the microbes of tetanus and of gangrene."

"Prof. Robert Koch, the eminent bacteriologist, employs photography with great success to bring out the most minute parts of organic and inorganic bodies. He likens the negative plate to a human eye not blinded by long-continued examinations. 'The negative,' says Prof. Koch, 'frequently shows very fine bodies and parts, which are afterward discovered by the microscope on the object itself, but only after very hard work and under the most favorable conditions.' "

"A.S.Q. says: Suppose a man to fall overboard from a vessel in midocean, water very deep; will he go to the bottom, or after having reached a certain depth, will the water be too dense to allow of his sinking further? *A. There is every reason to believe that any body that will sink at all will sink to the bottom. The known fact that fishes live at the bottom of the deep seas, that water is but slightly compressible, and that organic bodies are equally or more compressible than water, sustains this view.*"

"Several bars provided with automatic distributors of hot and cold beverages are installed in different parts of Paris. We give a representation of one that is in operation at 32 Montmartre Street. The distributor presents externally the appearance of two superposed kegs. The upper keg protects a glass bottle containing the supply of liquid. The lower keg conceals the entire mechanism. The work produced by the fall of the coin from the slot into the pan effects the starting of the mechanism and the opening of the cock."

Automatic beverage distributors

DRAMBUIE IS MADE WITH THE FINEST INGREDIENTS. (BUT WE CAN'T TELL YOU WHAT THEY ARE.)

The secret of Drambuie begins with a manhunt. It is winter, 1746. Scottish rebel leader Bonnie Prince Charlie is fleeing for his life from the English. Helped to safety by the MacKinnon clan chief, he thanks the old man with a curious gift: the recipe for his personal liqueur.

The drink that became Drambuie.

To this day, only one MacKinnon in each generation knows the formula.

He will admit the presence of rare 15 year old malt whiskies.

He will explain that Drambuie is sweet and mellow on its own, slightly drier over ice and a match for any mixer.

But ask him about a certain herbal essence and he will say to you precisely what he has said to us.

Nothing. Not a single word.

STILL MADE TO THE PRINCE'S SECRET RECIPE.

High and Dry

New wetlands policy is a political quagmire

WETLANDS in areas of Nisqually National Wildlife Refuge would lose their designation under the 1991 proposal. Photo: Andrew McMillan.

It seemed easy enough. Armed with copies of the Bush administration's recently proposed wetlands guidelines, a group of scientists set out to reevaluate 22 of Washington State's recognized wetlands. They visited Nisqually and Turnbull national wildlife refuges as well as Bowerman Basin—each a famous wetland and breeding site for migrating birds.

To their surprise, large parcels of the parks would no longer qualify if the regulations are approved. In fact, under the new rules only four of the 22 wetlands would be so classified. "If a team of regional experts can't determine a known wetland, how can the public?" asks Michelle Stevens of the Washington State Department of Ecology, who participated in the review.

Like Stevens, scientists all over the country are having trouble deciphering the guidelines. The new wetlands policy, which was announced this August and is under review until December, promised to continue the president's "no net loss" campaign and to make these dwindling resources easier to identify—and to protect.

But many experts say the document is filled with inconsistencies and loopholes that could lead to the loss of designation for half of the nation's remaining wetlands. The debate has also raised questions about the role of politics in a scientific process. "It is the height of arrogance to have [Vice President] Quayle's staffers think they can write a wetlands manual," asserts Tim Searchinger, an attorney at the Environmental Defense Fund, one of the groups opposing the policy.

The 1991 proposal is the latest in a series of wetlands preservation documents. These areas first received federal protection under the 1972 Clean Water Act. And in 1985 the Swampbuster program withheld subsidies from farmers who drained wetlands for agriculture. Despite these regulations, each agency involved in wetlands management—the Army Corps of Engineers, the Fish and Wildlife Service, the Soil Conservation Service and the Environmental Protection Agency—used different guidelines to define a wetland.

Finally, in 1989, the four agencies created a joint manual—but several special-interest groups objected. Farmers claimed that mostly dry land suddenly qualified as wetlands. Oil companies were concerned that even more of the Alaskan tundra would become protected wetlands. But in general, scientists were pleased with the document—finding it easy to use and logically developed. Although "we knew there were problems," explains William S. Sipple, chief ecologist in the EPA's wetlands division, "we also knew there were ways in which to improve it."

Sipple never got his chance. The revision process was transformed into the creation of new guidelines, and Sipple resigned from the interagency committee responsible for improving the manual. "This '91 thing is so horrendous and so bad," he says. "It is an embarrassment to the agency." Meanwhile the new policy was applauded by an industry group called the National Wetlands Coalition—members include Amoco, Arco, Chevron, Conoco and Exxon—that was influential in advising the White House staff on the proposed policy, according to government sources.

Roughly defined, wetlands are areas often covered by shallow water or areas in which soil is saturated. They serve as natural filtration systems, as repositories for floodwater and as fertile, frequently economically lucrative habitats for fish and wildlife. Although there are many kinds of wetlands—including prairie potholes, coastal salt marshes, bogs, swamps and vernal pools—they are often characterized by special plants that can grow and thrive in wet conditions.

Until their importance for water purification and flood control was recognized in the 1960s, wetlands were often drained or filled so they could be farmed or developed. A 1991 study by the Department of the Interior found that only an estimated 103.3 million acres of the lower 48 states' original 221 million acres of wetlands remained by the mid-1980s. Every year some

NEW

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The LEICA R-E: a new SLR camera with universal aperture priority mode designed for uncomplicated photography. Exposure time is set automatically while aperture preselection offers the freedom to compose with depth of field as the essential creative element. Together with the new zoom lens VARIO-ELMAR-R 28–70 mm, the LEICA R-E is the ideal SLR camera for photography that is uncomplicated. At the same time, focal lengths ranging from wide-angle to small tele open up a fascinating dimension of creative photography. Leica Photography.

Leica

The freedom to see.

300,000 more acres are lost, according to the National Audubon Society. The Washington State results—which are officially restricted by a gag order—as well as those from other regions, suggest that as many as 50 million acres would no longer be protected if the proposal is accepted.

The loss of wetlands has ramifications beyond poor water quality and flooded basements. Coastal wetlands curb erosion and provide nurseries for fish and shellfish. A 1987 National Wildlife Federation study reported that 45 percent of endangered animals and 26 percent of endangered plants depend indirectly or directly on wetlands. "Wetlands are frequently the places where there is the greatest biodiversity," notes William Schiller, a botanist at the American Museum of Natural History.

At the heart of the issue are definitions of three components of wetlands: hydrology, or wetness, vegetation and soil. Because the character of wetlands varies not only from region to region but from season to season, experts say it is not always possible to find all three aspects together. Indeed, under 1989 guidelines, two criteria could be used to infer a missing third. So, for example, if wetlands soil and vegetation were present, hydrology could be inferred and the area would be considered a wetland and subject to protection.

In contrast, under the 1991 manual, not only do all three criteria have to be present, each has to be described in resplendent detail. Many scientists say this demand would be problematic. For example, prohibitively extensive information on plants would be needed and soils would require the trained eye of a certified soil taxonomist—a rarity.

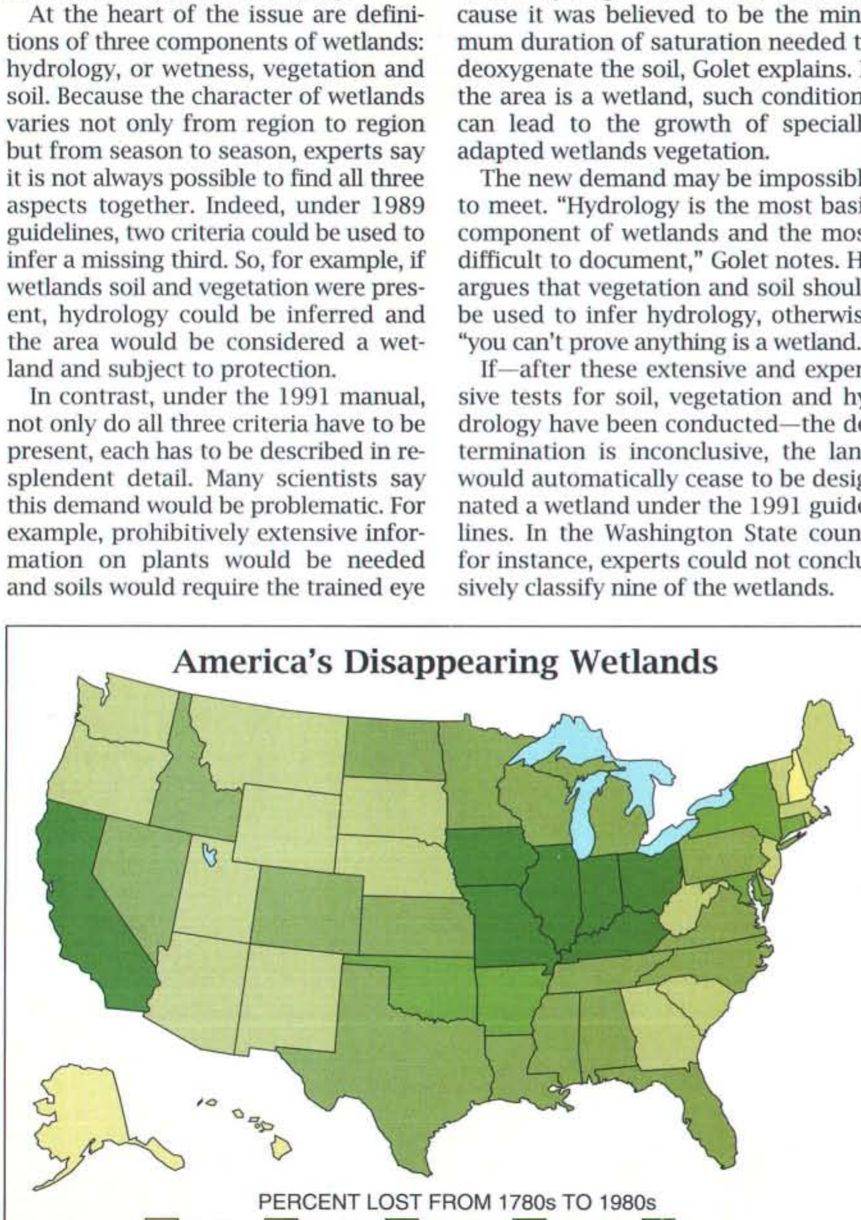
Once scientists completed the task of classifying soil and vegetation, they would be faced with hydrology. Perhaps the loudest criticisms of the proposed manual concern saturation. Under the new guidelines, land would have to be continually wet at the ground surface for at least 21 days or inundated for a minimum of 15 consecutive days to qualify as a wetland. The 1989 manual required that the land be saturated within six to 18 inches of the surface—for seven days.

The 21-day requirement has no scientific basis, says Francis C. Golet of the department of natural resources science at the University of Rhode Island, who worked on the first federal definitions of wetlands in the late 1970s. The seven-day requirement first arose because it was believed to be the minimum duration of saturation needed to deoxygenate the soil, Golet explains. If the area is a wetland, such conditions can lead to the growth of specially adapted wetlands vegetation.

The new demand may be impossible to meet. "Hydrology is the most basic component of wetlands and the most difficult to document," Golet notes. He argues that vegetation and soil should be used to infer hydrology, otherwise "you can't prove anything is a wetland."

If—after these extensive and expensive tests for soil, vegetation and hydrology have been conducted—the determination is inconclusive, the land would automatically cease to be designated a wetland under the 1991 guidelines. In the Washington State count, for instance, experts could not conclusively classify nine of the wetlands.

America's Disappearing Wetlands



SOURCE: U.S. Department of the Interior, 1990

Enforcement may also become more difficult. Under the old guidelines, the burden of proof was on the owner to show that land was not a wetland in order to obtain a permit from the Army Corps to develop the property. The 1991 proposal places the onus on the federal agencies to prove the land is a wetland. The new manual "gives very good guidelines to people to go out and violate the Clean Water Act," comments Kathy Kunz, a wetlands ecologist with the Army Corps. In the future, "we can't be as reliant on similar or neighboring areas to determine if something that has been filled was a wetland."

The new guidelines are not the only assault on wetlands management. Several bills pending in Congress would alter the definition and the relative value of wetlands. And a little-noticed bill passed this fall requiring the Army Corps to use its guidelines that preceded the 1989 joint agreement—until the 1991 proposal is worked out. The consequences are unclear. Some scientists argue that the earlier document is as protective as the 1989 one; others say it is open season on wetlands filling.

For its part, the administration says the revisions are scientifically sound. "There admittedly were some policy judgments made," says Michael R. Deland, chairman of the White House Council on Environmental Quality. "But there is no scientific consensus on this issue, as there seldom is on any environmental issue." Deland adds that the revisions are only part of a package that includes mitigation banking—trading credits for wetlands. Mitigation could ensure that anyone who destroys a wetland must create a similarly sized wetland somewhere else.

At present, however, creating self-sustaining wetlands does not seem entirely feasible. "We know that 50 percent of the attempts to create wetlands have failed to even grow wetlands vegetation," notes Joseph S. Larson, director of the Environmental Institute at the University of Massachusetts at Amherst. In contrast, Larson says, restoration is more successful—usually you just have to restore the water source. Then "you can take advantage of the soil and maybe the seeds" in the soil.

Perhaps because of the outrage expressed by scientists in the field who have to test the new manual and by environmental groups, the public comment period was recently extended. A larger concern still remains unaddressed. "They shouldn't be changing the definition of wetlands—that's a scientific issue," Golet says. But as one federal scientist notes: "So far it's policy one, science zero." —*Marguerite Holloway*

People Preserves

Apartheid's legacy pits wildlife against settlement

Petrus Nkosi's home is a stone's throw from the banks of the Crocodile River, whose waters divide the mud-and-tin shanties of Matsulu Township from Kruger National Park. This game reserve, one of the largest in the world, shelters some of the last protected rhinoceroses and elephants on the earth. It is the premier example of South Africa's conservation effort, which includes more than 560 national parks and nature reserves and whose land area comprises more than 7.2 million acres. Besides big game, these reserves contain the highest number of plant species per acre in the world and the largest number of surviving reptiles on the continent.

But Nkosi views the park and its custodians in a different light. He hobbles on crutches; there is a hole in his knee that still festers with pus two years after Kruger Park rangers shot him for poaching buck in the reserve. "Look at me. I am finished. I cannot find work. I cannot feed my children," Nkosi laments. "They can shoot us dead even if we are hunting for a small animal to feed our families. This makes people feel that animals are more important than our lives."

Like Nkosi, black people in most rural areas consider game reserves and the paramilitary personnel who run them to be symbols of apartheid repression. Poachers face the risk of being shot, even if their only aim is to feed their families. Park rangers, frequently drawn from the ranks of the South African Defence Force, are heavily armed and trained to shoot on sight. Illegal trophy hunters, organized syndicates in search of ivory and rhino horn, face between three and 10 years in jail, or worse. "We had poachers in 1982 and 1983," boasts Anthony Hall-Martin, chief research officer for Pretoria's National Parks Board, "and we killed them off."

The establishment of most game reserves entailed the forced removal of local villagers whose livestock and farming posed a threat, in the eyes of the country's rulers, to indigenous flora and fauna. Skukuza, the name given to the first and most famous rest camp in Kruger Park, translates as "He Who Sweeps Clean." That was the title bestowed on Major James Stevenson-Hamilton, the park's first ranger, by Tsonga tribespeople forced to abandon their villages so that the reserve could be fenced off at the turn of the century.

Contemporary examples abound. Some 100 kilometers north of Johannesburg lies the beautiful Pilanesburg Reserve. Inside its fences, one can still see the remains of homesteads whose residents were removed in the early 1980s to make way for the park.

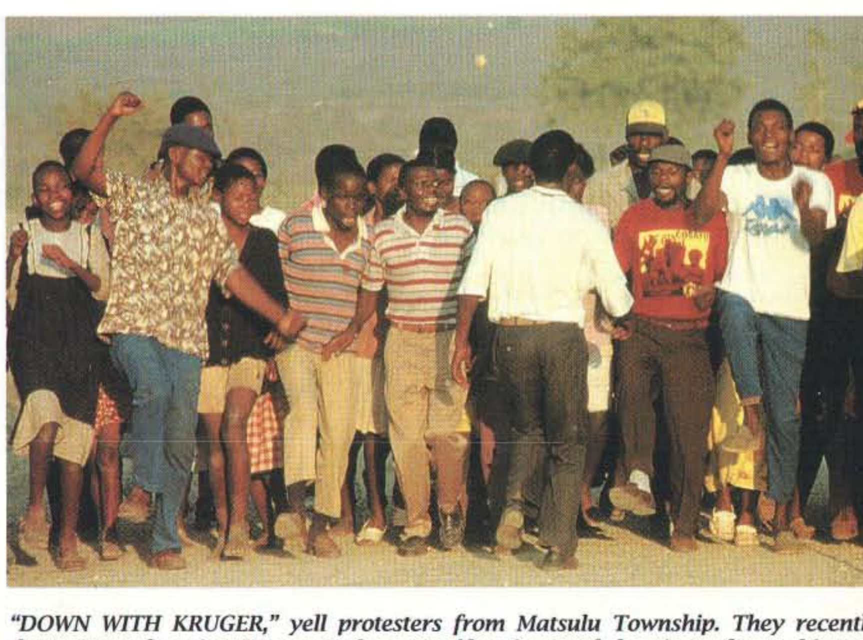
Game reserves are also deeply intertwined with the operations of Pretoria's military and its efforts to prevent cross-border incursions into the country. Many, including Kruger Park and the Ndumu Game Reserve in Natal, straddle the border with Mozambique and are still used by the army as a *cordon sanitaire* for keeping out illegal immigrants. Until recently, two reserves have been used by the South African Defence Force as missile testing sites. The De Hoop Reserve in the western Cape, where South Africa and Israel have jointly developed a long-range rocket capable of carrying nuclear warheads, is still a military zone.

As apartheid has begun to founder, rural communities are beginning to reoccupy the land or demand compensation for that which was taken from them. Local conservationists and politicians are still afraid of the way some Namibians celebrated independence from South African rule: they raced into the Etosha Game Reserve in the north of the country with guns and trucks and poached as much wild game as they could. "This is forcing conservationists to look at new ways of running these areas, to adapt to the new era of change in South Africa," says John Hanks, executive director of the Southern African Nature Foundation.

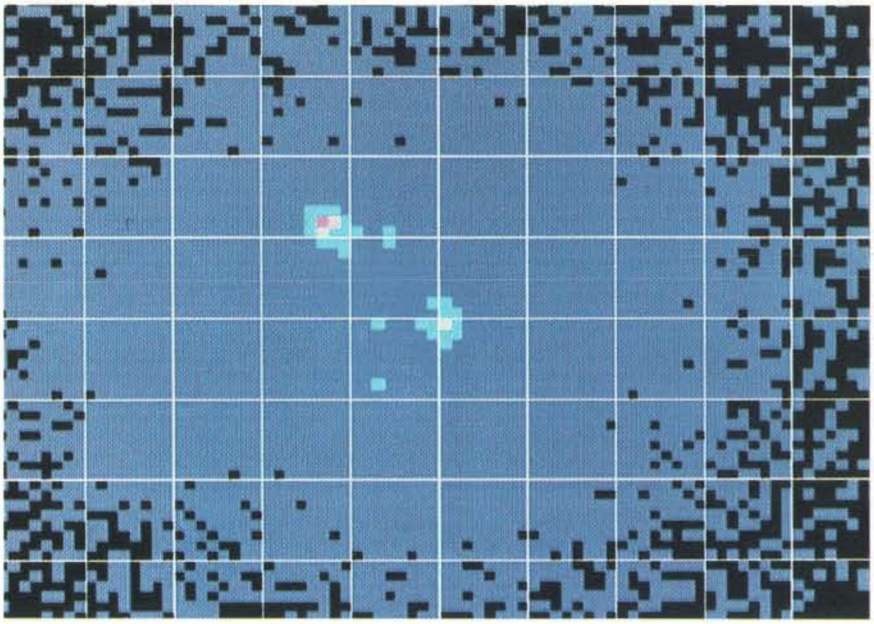
For the first time, a government-run game reserve has been created without any disruption to the lives of the people living in the area. In South Africa's newest reserve, the Richtersveld National Park in the arid northern Cape, seminomadic pastoralists have been allowed to stay; limited stock farming will be allowed in the reserve, and agreements have been negotiated that will protect unique plant species.

Earlier this year four prominent conservationists, including a senior official from the National Parks Board, feted African National Congress leader Nelson Mandela by hosting a hunting safari for him in the bush near Kruger Park. Mandela, heartened by the changes he has witnessed, favors retaining the existing network of parks and reserves. He would like to investigate ways in which the existing 6 percent of land allocated to conservation could be increased to meet recommendations from the International Union for the Conservation of Nature, headquartered in Geneva, that every country set aside at least 10 percent of its territory for the maintenance of biodiversity.

Notwithstanding memories of more than 40 years of forced removals, Mandela voiced support for the existing system of national parks. "Kruger Park is now an established fact whether we like it or not," he proclaims. "It has succeeded in preserving valuable wildlife and plants and other biological specimens. It has become one of our natural riches, and therefore we will have to preserve it."—*Eddie Koch, Johannesburg*



"DOWN WITH KRUGER," yell protesters from Matsulu Township. They recently demonstrated against Kruger Park rangers' beatings and shootings of township residents who entered the park to poach game or search for firewood. Photo: Bruce Wills.



GAMMA-RAY IMAGE captured by **Compton** *shows the Crab Nebula* **(right)** *and the enigmatic source known as Geminga* **(left)**. *Photo:* NASA.

Star Bursts

The deepening mystery of the gamma-ray sky

Every few hundred years or so a supernova appears whose light briefly exceeds that of any other star in the sky. Seen through gamma-ray eyes, the universe is far more dynamic: bright flashes of energetic gamma radiation, each lasting from thousandths of a second to a hundred seconds, appear everyday.

Over the past two decades, astrophysicists have developed a fistful of clever theories to explain these flashes, known as gamma-ray bursts. But in a dramatic press conference in late September, scientists reported that fresh observations by the National Aeronautics and Space Administration's *Gamma Ray Observatory,* recently renamed the *Compton Observatory,* show that bursts and other gamma-ray phenomena behave in ways that continue to defy explanation.

Most models posited that bursts resulted from matter falling onto a neutron star (an ultradense stellar corpse) or from some temporary instability of the neutron star itself. Because neutron stars are distributed throughout the galaxy, theorists expected that bursts—especially the faintest, most distant ones—would appear to cluster along the plane of the galaxy, much like the faint stars that make up the luminous band of the Milky Way.

By the time of the conference, one of *Compton's* highly sensitive detectors, known as the *Burst and Transient Source Experiment* (*BATSE*), had detected 117 bursts. Much to everyone's surprise, the bursts are spread almost perfectly evenly across the sky, which seems to suggest that they are not a part of our galaxy. "The most popular explanation of gamma-ray bursts is dead or in need of serious revision," concludes Neil Gehrels of the Goddard Space Flight Center, *Compton's* project scientist.

Equally puzzling, *BATSE* also found a cutoff in burst brightness. The absence of extremely faint bursts implies the existence of a boundary beyond which no bursts can be observed; the most obvious such boundary is the edge of the Milky Way. But if bursts are not scattered throughout the galaxy, they must be either fairly local phenomena (in which case the existence of a boundary is quite mystifying) or incredibly luminous events in distant galaxies (in which case the boundary may represent the visible edge of the universe).

Many astrophysicists are not about to give up on the neutron-star model just yet. Marvin Leventhal of AT&T Bell Laboratories speculates that some neutron stars lie far outside the plane of the galaxy; these stars could create bursts when they encounter dark matter in the galactic halo. Richard Lingenfelter of the University of California at San Diego sees a simpler explanation for the results from *Compton.* He thinks *BATSE* is detecting two kinds of gamma-ray bursts, a faint population that is sufficiently nearby to appear isotropic and a second, less common group of much brighter but more distant flashes. Both could be explained by present neutron-star models, he asserts.

Bohdan Paczynski of Princeton University, one of the few researchers who never subscribed to the neutron-star model, suspects that the bursts actually lie far outside the Milky Way. "Some people are not persuaded," he admits, "but the reasons are mainly psychological." He derides attempts to save the neutron-star model as "adding epicycles." Paczynski proposes that rare but extremely energetic encounters between neutron stars and black holes could create blasts of gamma radiation that would be readily visible even if they originated in distant galaxies.

A much more complete map of bursts, which will be available in a year or two, will permit a better evaluation of their true distribution. If gamma-ray bursts truly do originate in remote galaxies, *BATSE* should eventually see flashes whose images have been split by the gravity of intervening galaxies. These doubled bursts should look identical but show up a few weeks apart.

The *Compton Imaging Telescope* (*COMPTEL*), another instrument on board the *Compton Observatory,* may help solve the mystery of the bursts. *COMPTEL* has captured the first crude images of a gamma-ray burst in the act. Images from *COMPTEL* will enable astronomers to point their telescopes to the exact location of a burst to see if any object is visible at other wavelengths. And several instruments on board *Compton* are recording the energy distribution and very short term behavior of bursts, which should constrain some of the numerous models that theorists are considering.

Researchers will also have their hands full trying to solve other puzzles raised by the satellite's first batch of results. A pervasive gamma-ray glow emanating from the heart of the Milky Way, until recently thought to be the combined radiation from a multitude of supernova remnants, turns out to be inexplicably concentrated toward the center of the galaxy. And an enigmatic object known as Geminga shows up at the highest-energy gamma rays but is invisible at all lower energies.

"We didn't expect to have anything to report so soon," Gehrels says, "but the scientific return from the first few months of the mission has been spectacular." Astrophysicists expect that before its mission is over, *Compton* will completely redraw the map of the gamma-ray sky. —*Corey S. Powell*

Fatal Flaw

Who will have the right to examine your genes?

A graduate of a police academy in the Midwest was about to be hired as a policeman when it became known he had a family history of Huntington's chorea, an incurable disorder that causes physical and mental degeneration in middle age. The man was told he would have to be tested for the gene causing the disease before he could be hired.

Such testing by employers and insurance companies is not yet common, but new genetic discoveries that make it possible are being reported almost weekly. Researchers are rapidly expanding the list of specific genes carried by many healthy people that are statistically linked to an increased risk of acquiring one or another disease, including many cancers and other disorders not normally thought of as genetically based.

One current target for investigators is an inherited form of breast cancer that will develop in about one in 170 women before they reach the age of 50. According to Mary Claire King, a researcher at the University of California at Berkeley, that statistic makes inherited breast cancer more common than such well-known genetic diseases as cystic fibrosis and muscular dystrophy. By analyzing the genetic constitution of afflicted women, King is rapidly winnowing down the shortlist of genes found in one region of chromosome 17 that might transmit a tendency to acquire the malignancy. When King or some other researcher succeeds, developing an easy-to-use test will be relatively simple.

King, who described her latest results in October at the 8th International Congress of Human Genetics in Washington, D.C., hopes her research will lead to ways to diagnose breast cancer at an early stage, when it is more easily treated. Knowing the nature of the genetic changes that occur in cancerous cells might, she points out, make it possible to develop a blood test that would betray the presence of tumors that are too small to be detected by present techniques, such as mammography.

Early treatment is better treatment, and many of the scores of recent discoveries in human genetics can be expected to benefit patients as care improves. Candidate genes for predispositions to Alzheimer's disease, colon cancer, liver cancer and some forms of arthritis have all recently been found. Carrier and prenatal genetic screening has already led to a dramatic drop in the number of babies born with severe genetic disorders, such as Tay-Sachs disease and beta thalassemia.

But as more tests become available, their use as a screening tool is likely to increase. According to a survey conducted by the congressional Office of Technology Assessment (OTA) and released in October, only 12 out of 330 Fortune 500 companies reported in 1989 that they were conducting genetic monitoring or screening, either for research or some other reason. But roughly half of the companies responding thought genetic monitoring or screening would be acceptable, either for the benefit of the employee or the employer. More than 40 percent of the companies admitted that the potential cost of insuring an otherwise healthy job applicant would affect his or her chances of being hired.

The main reason genetic screening is not more common, the OTA survey implies, is that personnel officers believe the tests now available are not cost-effective. Insurance companies, for their part, argue they should have access to any genetic information that is available to those they insure. Insurers would use that data to prevent people who know they are at an increased risk of illness or death from buying excess coverage. "There are already many examples of people who either have been denied insurance coverage or have had benefits limited because of dependents with genetic disorders," observes Paul R. Billings, a medical geneticist at California Pacific Medical Center in San Francisco.

Arguments over who should have access to information are not new. In the 1970s blacks in many states were screened against their will for the sickle cell trait, and some of those who refused to be tested were charged higher insurance rates. Many people who have a family history of Huntington's disease decline to be tested for the Huntington gene for fear that health and life insurance companies as well as employers might discriminate against them. Another issue is whether the relatives of patients carrying such genes should be given the test results.

Laws to prevent the abuse of genetic information are on the books in eight states, points out Philip R. Reilly, executive director of the Eunice Kennedy Shriver Center for Mental Retardation in Waltham, Mass. The Human Genome Project, the international effort to map and sequence the entire human genome, is often cited as a reason for enacting protective legislation. Wisconsin, Rhode Island, Pennsylvania and Texas are all debating measures to prevent misuse of genetic data, and commissions in several European countries have recommended legislation that would deny insurance companies access to genetic information.

By 1995, the Americans with Disabilities Act of 1990 will restrict preemployment medical examinations so that they can be used to determine only an applicant's ability to do the job. But that law will not affect insurers. "We may see increasing pressure to avoid the birth of children who will be costly to insure," says Neil A. Holtzman, a professor of pediatrics at Johns Hopkins University.

State assemblyman Lloyd G. Connelly of California recently sponsored a bill that would have prevented employers and insurers from discriminating on the basis of "genetic characteristics" associated with a risk of disease. Although the state's insurance industry dropped its opposition, the California Manufacturers Association fought the legislation to the end. Governor Pete Wilson vetoed the bill in October, saying he feared it would impose an undue burden on employers.

A subcommittee of the House of Representatives recently devoted a day of hearings to uses and misuses of genetic information and also examined the proposed Human Genome Privacy Act, introduced by Representative John Conyers, Jr., of Michigan. The bill extends the right of privacy to cover genetic information. Modeled on consumer credit laws, it would prevent genetic information about an individual from being made available to third parties without the person's consent. It would also give individuals the right to correct their records.

That is not protection enough, says Dorothy C. Wertz, a medical sociologist at the Shriver Center. "The bill says almost anyone can have access to genetic information with the patient's consent, and one can coerce consent," Wertz asserts. "It won't protect most people."

Some see the increasing availability of genetic testing—which reveals ever more differences between people—as posing a fundamental challenge to private insurance, which operates by pooling risk. "There are 37 million people in this country who are uninsured or underinsured," Billings notes. "Our system is geared to excluding people who will get sick. Until there is a fix, predictive genetic tests that identify presymptomatic people will make this situation worse." —*Tim Beardsley*

The Ig Nobel Prizes

Irreproducible achievements finally get what they deserve

Forget Sweden. This past October crowds descended on the campus of the Massachusetts Institute of Technology for the first annual Ig Nobel Prize Ceremony. With heads raised high and tongues in cheek, a procession of pranksters and researchers set out to skewer the most ignominious accomplishments in science.

The evening was sponsored by the M.I.T. Museum and the *Journal of Irreproducible Results,* a humor magazine that lampoons research papers. As explained by Marc Abrahams, the editor of the *Journal* and master of ceremonies for the awards, the Ig Nobel Prizes are presented to persons whose work cannot—or should not—be reproduced.

Four Nobel laureates—Sheldon L. Glashow and Dudley R. Herschbach of Harvard University and Eric S. Chivian and Henry W. Kendall of M.I.T.—presided over the event, all attired in the silly hats and fake noses befitting the dignity of the occasion. Laureate Jerome I. Friedman of M.I.T. was there in spirit: he sent a slide of himself with a recorded message that congratulated the winners and added, "I hope you're enjoying the evening as much as I am."

The Ig Nobel Prize in Chemistry was awarded to Jacques Benveniste of the French National Institute of Health and Medical Research for his 1988 paper in *Nature* that claimed water had a memory for materials dissolved in it. The education award went to Vice President Dan Quayle, hailed by Abrahams as a "consumer of time and occupier of space," who had clearly demonstrated the need for a good science education.

Thomas Kyle of M.I.T. won but declined the physics prize for his paper in the *Journal* describing administratium, the heaviest element in existence, which consists of one neutron, eight assistant neutrons, 35 vice-neutrons and 256 assistant vice-neutrons. Kyle explained he had not actually done any of the research: in the true spirit of science, he had just signed his name to the publication.

The winner of the Ig Nobel Peace Prize was Edward Teller of Lawrence Livermore National Laboratory. As the father of the atom bomb and the originator of the "Star Wars" Strategic Defense Initiative, Abrahams noted, Teller had done the most "to change the meaning of peace as we know it."

Imprisoned junk-bond dealer Michael Milken, "to whom the world is indebted," walked away with the laurels for economics. Erich von Daniken, author of *Chariots of the Gods* and other books that claim alien astronauts visited Earth in prehistory, received the prize for literature. And the prize for biology was awarded to Robert Klark Graham of the Repository for Germinal Choice in Escondido, Calif., a sperm bank that accepts deposits only from Nobel laureates and Olympic athletes.

Perhaps the most noteworthy parties overlooked by the Ig Nobel Prize committee were B. Stanley Pons of the University of Utah and Martin Fleischman of the University of Southampton, the discoverers of cold fusion. There's always next year. *—John Rennie*

AT THE IG NOBEL AWARDS, Nobelists S.L. Glashow, E.S. Chivian, D.R. Herschbach and H.W. Kendall **(seated left to right)** *pay their respects. Photo: Stanley Rowin.*

Cross Reaction

Could AIDS really be an autoimmune disease?

The standard picture of AIDS infection is that the virus simply attacks and destroys so-called *T4* cells, a crucial component of the immune system. But a few researchers have been impressed by the similarity between the clinical features of AIDS and graft versus host disease. This often fatal condition develops when transplanted immune system cells, such as those in bone marrow, attack their new host—including the suppressor *T* cells that regulate the immune system.

Two studies with experimental animals have recently produced surprising results that add to credibility of theories that AIDS might have much in common with graft versus host disease. The findings, if confirmed, could have important implications for efforts to develop a vaccine to protect people against infection or to reverse the deterioration of the immune system in those who are already infected. Although neither finding casts doubt on the central role of HIV infection in causing AIDS, both suggest that immune responses to foreign cells may be important as well.

Angus G. Dalgleish of St. George's Hospital in London and John A. Habeshaw of the Royal London Hospital have argued for some years that HIV infection makes the immune system attack itself. Dalgleish and Habeshaw believe the coat protein of HIV, known as GP120, generally inhibits the immune system. GP120 also chemically resembles parts of the class II major histocompatability complex (MHC), molecules that identify immune system cells as host cells. The similarity, Dalgleish says, permits a cross reaction in which the immune system attacks host cells as it would foreign cells. The resulting syndrome resembles graft versus host disease.

Tracy A. Kion and Geoffrey W. Hoffmann of the University of British Columbia have a related idea. They point out that many people who are infected with HIV might also have been exposed to "foreign" immune system cells—cells from another person—in body fluids. They believe that people who have been exposed both to foreign cells and to HIV launch two distinct kinds of immune response, one against the cells and one against the virus. Each response also attacks a subgroup of *T* cells, helper and suppressor cells, fatally destabilizing one of the immune

system's self-regulatory mechanisms, leading it to destroy itself.

Kion and Hoffmann have now buttressed those ideas with experimental observations. They published in *Science* evidence that mice that have been exposed to cells from a different mouse strain spontaneously produce antibodies to GP120 as well as to an HIV core protein—even though they have never been exposed to HIV. The mice also made antibodies that resembled MHC molecules, just as the theory predicts.

Moreover, mice that are specially bred to develop an autoimmune disease similar to lupus erythematosus also spontaneously made antibodies to GP120, as well as MHC-like antibodies. The fact that mice could produce antibodies to GP120 without ever having been exposed to HIV suggests that there is indeed a significant similarity between GP120 and molecules normally operating in the immune response.

The second study, published recently in *Nature*, indicates that macaque monkeys can be protected against infection with the simian immunodeficiency virus (SIV) simply by immunizing them with human *T* cells. Researchers led by E. James Stott of the National Institute for Biological Standards and Control in England had expected to see a protective antibody response only when the macaques were immunized with *T* cells that had been infected with SIV.

Instead macaques that produced high levels of antibodies after being immunized with human *T* cells were protected against subsequent infection with SIV—whether or not the *T* cells were infected with the SIV virus. "Rather to our surprise, there was no connection," Stott says.

Dani P. Bolognesi, a leading U.S. AIDS researcher who works at Duke University Medical Center, says he has already confirmed Stott's finding that macaques with high levels of antibodies against foreign cells are protected against SIV infection, although he has not yet done the experiment using uninfected cells. The key question that must be answered next if the approach is to lead to a vaccine, Bolognesi says, is whether the "Stott effect" works when macaque cells, rather than human cells, are used to immunize macaques.

Dalgleish, for his part, says Stott's results provide indirect support for his ideas. He says he will shortly publish new studies showing extensive similarities between GP120 and class II MHC molecules. He hopes the British Medical Research Council—which has previously rejected his grant applications as too speculative—will now take more notice. —*Tim Beardsley*

Smaller World

The Draper Prize recognizes the fathers of the jet age

In the early 1950s it often took passengers 14 hours to cross the Atlantic in a propeller-driven airplane. Trans-Atlantic jet flights, which began in 1958, cut that time in half. The jet age, however, had actually begun about 20 years earlier.

During the 1930s, a British and a German engineer, each unaware of the other's work, designed and built prototypes for the turbojet engine. The German, Hans J. P. von Ohain, who was then employed by German aircraft manufacturer Ernst Heinkel, was the first to see his engine propel an aircraft aloft during a seven-minute flight on August 27, 1939. The first aircraft powered by an engine built by British entrepreneur Frank Whittle flew in 1941, although he had received a patent as early as 1930.

The two men, who in their own way brought the world's nations a good deal closer, will now split a $375,000 check. In October the National Academy of Engineering (NAE) announced that Whittle and von Ohain have become the second recipients of the Charles Stark Draper Prize, to be presented in February. The first award went to Robert N. Noyce (who died in 1990) and Jack S. Kilby, the inventors of the integrated circuit.

NAE officials would like to see the Draper award achieve a standing in engineering comparable to that of the Nobel Prizes in science and literature. "Too often engineers are too modest about their work and so don't always get the recognition that they should," says Robert M. White, president of the nonprofit organization in Washington, D.C., that advises the U.S. government on engineering and technology. "And we hope that the Draper Prize will put a well-deserved spotlight on engineering."

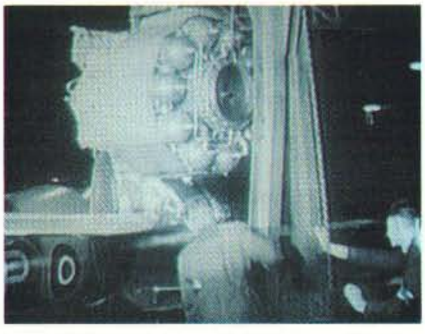
The prize is awarded for engineering contributions to "human welfare and freedom." Jet planes, of course, are used to deliver foodstuffs and emergency medical supplies, besides carrying business travelers and innumerable overnight packages. But, paradoxically, the first use for the new jet airplanes was military: German and British jets saw limited combat toward the end of World War II, although the planes never met each other in a dogfight.

The endowment for the prize comes from the Charles Stark Draper Laboratory in Cambridge, Mass. Previously affiliated with the Massachusetts Institute of Technology, the laboratory has been known for its work in guidance systems, such as the one for the Trident II missile. It is named for the inventor of the inertial guidance system; Draper died in 1987.

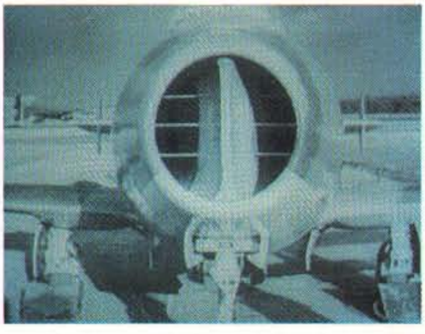
The two Europeans did not have to cross the Atlantic by jet to be present when the winners were made known. The 79-year-old von Ohain was recruited by the U.S. Air Force after the war to work on jet propulsion at Wright-Patterson Air Force Base, where he eventually became chief scientist of the Aero Propulsion Laboratory.

In 1979 he moved to the University of Dayton Research Institute, where he is still a senior research engineer. Whittle, now 84 years old, continues to hold British citizenship, but he has taught at the U.S. Naval Academy in Annapolis, Md., since 1977.

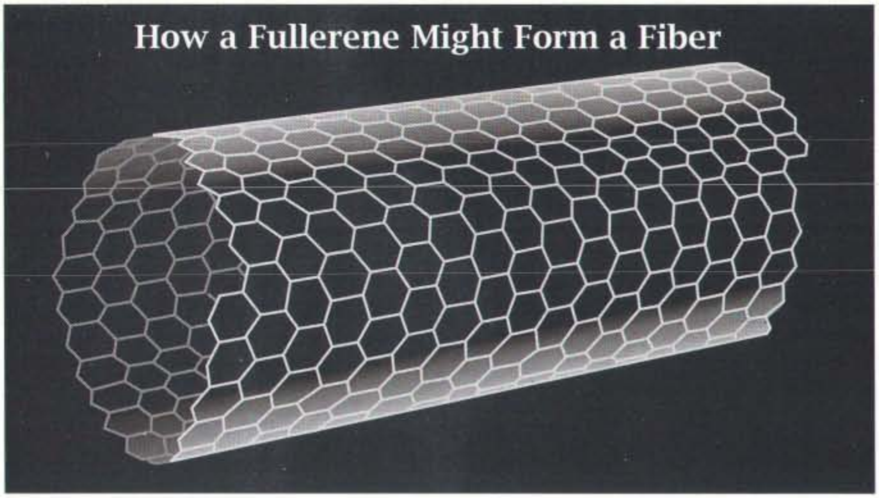
The former war foes are now fast friends. Von Ohain explained to the press how one of Whittle's great accomplishments was to convince the British Air Ministry that a gas turbine could produce the thrust needed for jet propulsion. Others had discarded the idea. Asked why he believed it was possible to build a machine others thought to be a practical impossibility, Whittle retorted, "Well, I was too stupid to know that it wouldn't work." —*Gary Stix*



TURBOJET ENGINE is being fitted into the Gloster-Whittle E.28/39 aircraft during the spring of 1941.



AIR INTAKE on the Gloster-Whittle reveals the hollow fuselage where Whittle's engine is lodged.



Buckytubes

Fullerenes may form the finest, toughest fibers yet

The family of carbon cages known as fullerenes has already shown a vast range of mechanical, chemical, magnetic and electrical properties, including high-temperature superconductivity. Now a Japanese scientist has found yet another attribute of these clusters: they apparently form tubes that are thinner, more perfect in their molecular structure, more resistant to chemical attack and almost certainly stronger than any other fiber.

Sumio Iijima, a scientist at NEC Corporation, made the discovery this past May while examining sooty deposits on a carbon-arc electrode he had used to generate fullerenes. There he found tiny, tubular fibers, up to a micron long, tiled in hexagonal arrays that tightly bind the carbon atoms and that terminate in faceted, conical caps. His first paper describing the tubes was scheduled to be published in *Nature* in early November.

Because the family is named for its 60-atom archetype, buckminsterfullerene, or buckyball, Iijima's fiber was quickly dubbed buckytube. "It has a very interesting structure—to me much more interesting than buckyballs," Iijima says. "First, it is helical—such structures have never been found before in inorganic material. Second, it is cylindrical—a very unusual crystal lattice." He later corrected himself, noting that Robert L. Whetten of the University of California at Los Angeles had proved that the fullerene C_{76} is helical. (Whetten says he thinks many or all of the larger fullerenes are helical.)

Iijima deduced the structure of his tubes in part from images produced by the 500,000-fold magnifications of a high-resolution transmission electron microscope, in part from electron diffraction patterns. The images showed cross sections of two or more coaxial tubes 0.34 nanometer apart—a distance roughly equal to the gap between layers of carbon atoms in graphite and to the radius of a buckyball.

The diffraction patterns indicate a crystalline structure of hexagonal carbon rings, such as are found in graphite sheets, but with a twist. The tubes are formed of sheets of hexagons whose rows look as if they had been curled up and pasted to those of a nearby row, creating a spiral.

Because the tubes enclose channels as small as two nanometers wide, they hold the possibility of weird physical properties. "It could be a quantum pipe," Iijima speculates, referring to a hypothetical structure through which electrons might "tunnel" effortlessly. "They could be superconducting. Who knows?"

The possible mechanical strength of buckytubes is a more immediate boon. "It could be the strongest fiber that exists, maybe the strongest that can exist," Iijima says. Its strength flows from the nature of carbon-carbon bonds, on the one hand, and the nearly flawless structure of the tubular crystals, on the other. "A carbon fiber is the strongest thing in nature, very stiff for its weight," says Mildred S. Dresselhaus of the Massachusetts Institute of Technology. "Buckyfibers have very few defects and so in that sense are better than graphite."

Dresselhaus in fact predicted the tubes before their existence became generally known, while discussing hypothetical molecules with Richard E. Smalley of Rice University, a fullerene pioneer. Smalley has since propounded the theory that buckytubes will heal their open ends when broken. He cites Leonhard Euler, the 18th-century Swiss mathematician, who proved that a hexagonal sheet of any size can close into a polyhedron only if it adds exactly 12 pentagons to the mix. Smalley draws a fascinating conclusion: if buckytubes are indeed closed—and hence true fullerenes—they might tend to "heal" themselves. A broken buckytube should tie up dangling bonds by producing new pentagons at the open end, thus closing it.

More interesting than how the fibers close is how they start growing in the first place. "The fibers have to be nucleated," Dresselhaus says. "They would start from clusters, but instead of becoming balls they grow like fibers." If such growth could be extended, fine-tuned and scaled to macroscopic yields, chemists would be able to cook up inch-long buckytubes having any number of layers.

Iijima says he is trying to optimize for length and for yield, but he just laughs when asked how he hopes to do it and what results he expects to obtain. He says he also wants to test the self-healing theory by administering a tube-busting jolt of electricity and seeing what happens at the break points.

Iijima's findings have not yet been reproduced. Yet word of his discovery only began to percolate through the international fullerene fraternity in mid-October, after Iijima gave a presentation at a conference held in Richmond, Va. Whetten says that if buckytubes are confirmed, researchers would begin reconfiguring their labs "in about a month."

The preliminary nature of Iijima's results did not stop many of the 200 or so participants at the Richmond conference from suggesting off-the-cuff applications. A physicist imagined arrays of parallel buckytubes functioning as a gamma-ray window, enabling the high-energy radiation to propagate through their pores while discouraging the diffusion of gases, such as air.

Engineers speculated about carbon fibers that would outperform graphite as a matrix for carbon-carbon composites, extremely strong and light materials used in high-performance aircraft. But graphite fibers are vulnerable to the slightest scratch, which opens the broken ones to oxidation. A buckytube composite capable of healing itself would retain its strength.

Science lags ever less behind fiction. David Jones, writing under the pen name Daedalus, imagined fullerenes 19 years before they were detected. In *Nature* this past June, he dreamed of superstrong "graphitic foam" made of carbon tubes—weeks after Iijima had discovered buckytubes. —*Philip E. Ross*

PROFILE: THOMAS EISNER

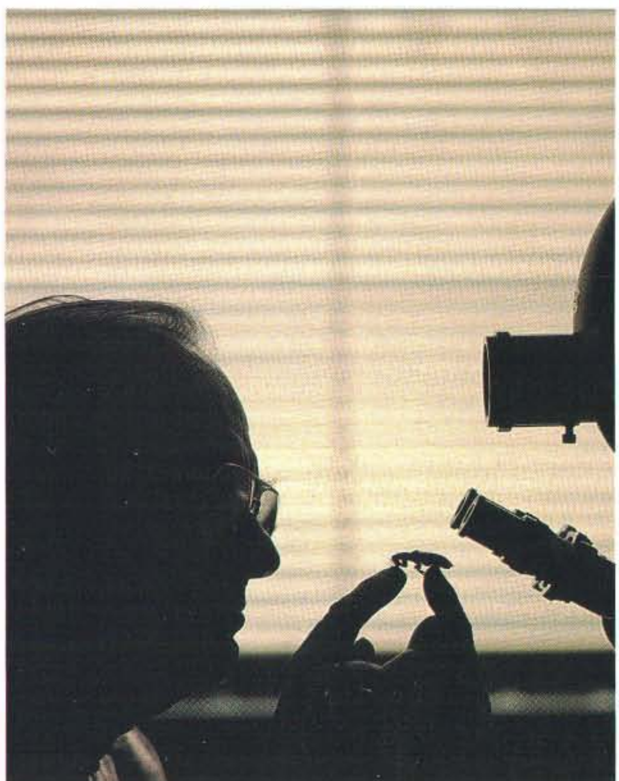
The Man Who Loves Insects

For more than an hour, Thomas Eisner has been making the case for a concept he calls "chemical prospecting." Nature, he asserts, is a vast, unexplored reservoir of potentially beneficial chemicals—remedies for cancer or diabetes or the common cold. By "mining" such compounds from plants, insects and other organisms, says Eisner, a professor of biology at Cornell University and pioneer of a field called chemical ecology, humans can offset the costs of conservation.

The wiry, fast-talking Eisner, who at 62 still sports long, 1960s-style sideburns, has been promoting this scheme a lot lately, to politicians and industrialists as well as to reporters, and his weariness shows a bit. As he pauses to rub his eyes, I remind him that he promised to show me some bombardier beetles, so called because of their ability to blast attackers with a high-pressure spray.

"Right!" Eisner exclaims. He bolts from his office and returns a minute or so later with a plastic box. Setting the box gently on his desk, he gazes down at its inhabitants—several dozen pinheaded, brownish bugs—with unalloyed affection. "Aren't they beautiful?" he asks.

Yes, let it be said: Thomas Eisner loves bugs. He has parlayed a childhood obsession into a career as a leading authority on insects, especially on the crucial role that chemicals play in insects' survival strategies. He reveals this phenomenon through marvelously evocative particulars: a male moth whose bitter diet makes it repugnant to spiders but alluring to female moths, or a female firefly that deceitfully beckons and then devours males of another species rich in a predator-repelling poison. The eminent entomologist and sociobiologist Edward O. Wilson of Harvard University, a former classmate of Eisner, calls him "the Seurat of evolutionary biology."



"A NOSE with a human being attached," Eisner excels at decoding insects' chemical signals. Photo: Robert Prochnow.

Eisner has interests other than insects. In addition to being a conservationist, he has worked for the rights of scientists in totalitarian countries and for population controls worldwide. An ardent musician, he plays the piano and conducts an amateur orchestra at Cornell. Its motto, he says, paraphrasing Mark Twain's comment on Wagner, is, "We're not as bad as we sound." But if Eisner had a bumper sticker on his car, it would almost certainly read, "I'd rather be bug watching."

Reality, it seems, has always intruded on Eisner's dalliances with bugs. He was born in Berlin in 1929 to a Jewish father and a Christian mother. When the Nazis rose to power in 1933, the family fled to Spain, where civil war soon erupted. In one of Eisner's earliest memories, he was sitting in a sandbox in Barcelona poking and peering at his favorite pets when a streetcar filled with dynamite exploded and careened into a nearby house. Eisner recalls being not terrified but annoyed "to find my playing with insects interrupted."

In 1937 the family left Europe and sailed to South America. They eventually settled in Montevideo, Uruguay, a paradise for the young insect fancier. He turned his room into a menagerie of tropical moths, beetles, spiders and ants. "No one else was daring to go in there," he boasts. "I had no need of playmates." After a moment's reflection, he adds, "I must have been very weird."

Eisner also grew up with an unusual sensitivity to and fascination for smells. "I'm essentially a nose with a human being attached," he remarks. He traces this trait to his father, a professional chemist who brewed perfumes at home. The young Eisner sometimes sniffed strangers on meeting them; he also noticed that many insects exuded pungent odors.

In 1947 the Eisners moved to New York City, and shortly thereafter the teenage Eisner applied to several prestigious colleges—in vain. (He delights in showing visitors his letter of rejection from Cornell, which hangs on the wall of his office.) Eventually his English improved (his first languages were German and Spanish), and after a stint in a two-year college he transferred to Harvard, from which he received his doctorate in biology in 1955.

In the 1950s, Eisner points out, biologists still had mere inklings of how secretions and emanations, flavors and smells, mediate insect behavior. Eisner's own interest in this possibility was sparked in part by an article on how honeybees tell nest mates of the whereabouts of nectar through elaborate "dances." Recalling the odd odors given off by his pet insects in Uruguay, Eisner wondered "how much could happen with chemicals rather than acoustic or visual signals."

After becoming a professor of biolo-

gy at Cornell in 1957, Eisner began exploring this question in earnest. Since chemistry was not his forte, he teamed up with an organic chemist at Cornell named Jerrold Meinwald, who remains his closest collaborator. (Meinwald also occasionally plays the flute in the "not as bad as we sound" orchestra.) "Whatever accomplishments I've had over the past 30 years are at least 50 percent a consequence of having worked with him," Eisner says.

The duo's discoveries typically arose from a simple observation by Eisner, one that provoked him to ask, like an obstinately curious child, Why? In one case, he noticed that a spider cut an ornate male moth out of its web rather than eating it. Why? The male moths, while still caterpillars, consume plants containing alkaloids that spiders find distasteful.

The alkaloids, Eisner and Meinwald established, also serve as a kind of cologne that helps the male moth attract a mate. "In order to be accepted at mating, he has to give her a promissory note about how much [of the toxin] he's got in store for her," Eisner explains. "If he doesn't have enough, she says, 'To hell with you.'" Why? Because the toxin in the male's semen is passed on to the female's eggs, protecting them from predators.

The tale of the flashy femme fatale unfolded when Eisner noticed that a pet hermit thrush enjoyed eating some species of firefly and spurned others. On investigating, Eisner and Meinwald determined that the rejected fireflies contained a poisonous steroid the other species lacked.

The researchers then found that females of a nonpoisonous species often attract and consume the males of a steroid-rich species by mimicking the flashing pattern displayed by females of the species during courtship. The imposter thus protects both herself and her eggs. "This whole business of being concerned about your offspring—concerned in quotes, I'm not implying consciousness or anything like that—is a wonderful insect story," Eisner says.

Yet another case of deceit and murder from Eisner's files involves the woolly aphid. The aphids, which have a waxy coating resembling sheep's wool, exude a nectar coveted by ants. The ants do not kill the aphids but keep them gathered in flocks, "milking" them for nectar and protecting them from predators.

While observing a flock of aphids, Eisner noticed that some members seemed to be scuttling about with abnormal speed. On closer inspection, he realized that the aphids were actually larvae of the green lacewing, a deadly predator of the aphids. The lacewing larvae, Eisner eventually learned, had covered themselves in the woollike wax they had ripped from the aphids. Thus concealed, both visually and olfactorily, from the watchdog ants, the lacewing "wolves" could devour aphids to their hearts' content.

Then, of course, there is that marvel of engineering, the bombardier beetle.

Conservation efforts are doomed to fail, Eisner says, if society does not confront the greatest threat to nature: overpopulation.

Eisner originally encountered it in graduate school, when he impulsively popped one in his mouth. He insists he was only following an august predecessor's example. "I can't be sure that it was a bombardier beetle, but Darwin describes popping this beetle in his mouth because he needed two hands to catch two other beetles." Darwin, like Eisner, felt a hot, irritating sensation in his mouth. "He was so startled, he lost the two beetles in his hands," Eisner remarks. "So much for greed and dexterity."

Over the subsequent years, Eisner and various collaborators, notably Daniel Aneshansley of Cornell, found that the beetle concocts its toxic spray by combining two chemicals in a reaction chamber in its abdomen. The intense heat generated by the reaction brings the mixture to a boil. No other biological process is known to generate such high temperatures.

After enlisting the aid of the late Harold "Doc" Edgerton of the Massachusetts Institute of Technology, the grandmaster of high-speed photography ("you make one of these little discoveries involving insects, and you end up discovering people," Eisner says), Eisner and his colleagues determined that the beetle squirts the scalding, pressurized liquid in a pulsed jet out of two steerable nozzles at the rear of its chamber. The design of the reaction chamber and nozzles resembles the engine of the German V-1 rocket. "The creationists have used it as an example of something that had to be created," Eisner says with a chuckle.

Eisner takes his opportunities for discovery where he finds them, whether in the woods near his house in Ithaca, N.Y., or at the Archbold Biological Station in Lake Placid, Fla., where he does much of his research, or at some other site. "Whenever I'm in an area where I'm finishing a program," he says, "I try to add another two days to the experience, and in those two days I do nothing but look around. That's when I feel like I'm eight or nine years old again." He has even turned a phobia of flying to his advantage. "If I'm driving, I can stop every 50 or 100 miles and look for interesting insects at the side of the road."

As Eisner's appreciation of nature has deepened, however, so has his fear for its future. He has been involved in conservation efforts throughout his career. Teaming up with Wilson, he lobbied successfully for the preservation of one of the Florida Keys in the late 1960s. In the early 1970s he helped to pass legislation preserving Texas's "Big Thicket" wilderness.

But increasingly, Eisner felt that he could not simply promote conservation for its own sake. In 1989 he began proposing that countries could derive some profit from their wildernesses by selling chemical-prospecting "licenses" to industry. "I feel very odd sometimes speaking like a market economist, but setting aside land for conservation purposes has consequences for the people living there."

Eisner has firsthand knowledge of the commercial potential of natural compounds. After all, he and Meinwald have found a millipede packing an alkaloid that is a potent insect repellent, a firefly rich in a substance resembling the cardiac stimulant digitalis and a beetle containing a chemical similar to a well-known sedative. In recent years, moreover, techniques for finding and synthesizing beneficial compounds have improved enormously.

With such arguments, Eisner recently helped to persuade the giant pharmaceutical manufacturer Merck to invest $1 million in a rain forest preserve in Costa Rica in exchange for access to chemicals extracted from the preserve. He hopes that other companies will follow Merck's lead.

Yet Eisner emphasizes that no matter how successful such conservation programs are, they will fail if humans do not learn how to curb their population growth. "If someone told me that there is a way of addressing overpopulation constructively, I would drop everything and dedicate myself to it."

Well, maybe not everything. Over the past few months or so, Eisner's promotion of chemical prospecting has kept him inordinately busy, but this weekend he plans to make time for bug watching. "I have a lab that I built right outside my house," he says. "Sunday I'll spend all day in there. I'm ready for a discovery." —*John Horgan*

SCIENTIFIC AMERICAN

Homeless Families

Single women with young children constitute the most rapidly growing segment of homeless persons. Emergency shelter can only partly ease the physical and psychological devastation experienced by these families

by Ellen L. Bassuk

Twenty-six-year-old Martha lives in a shelter with her daughter, Sarah, and son, Matthew. Martha, whose father regularly beat her, graduated from high school with honors and completed three years of college. Soon after she was married, her husband was imprisoned for theft. After his release, the marriage became violent and floundered, and over the course of three years Martha left her husband 15 times. Martha is withdrawn and reluctant to apply for a job or an apartment. She describes a deep and enduring sense of shame, particularly about her black and carious teeth—the result of many years without dental care.

Five-month-old Sarah is frail, listless and underweight. She cannot hold down her food, is unable to grasp a rattle and rarely vocalizes or smiles. Her brother, Matthew, who has moved seven times in his 15 months of life, is painfully shy. After arriving at the shelter, he stopped saying the few words he knew, refused to eat and had trouble sleeping.

Martha, Sarah and Matthew—who were interviewed during the course of a study I conducted with my colleagues at Harvard Medical School—are part of the fastest-growing subset of the homeless: families most often headed by women. These single-parent families now account for approximately 34 percent of the homeless population—an increase from 27 percent in 1985, according to a 30-city survey conducted in 1990 by the U.S. Conference of Mayors. Another study, conducted in 1987 by the Urban Institute, found that 23 percent of all homeless individuals are family members. Every night between 61,500 and 100,000 homeless children sleep in emergency shelters, welfare hotels, abandoned buildings or cars. Some sleep exposed to the perils of the streets.

The consequences of this situation are dire. During critical, formative years, homeless children lack the basic resources needed for normal development. They undergo experiences resulting in medical, emotional, behavioral and educational problems that may plague them forever. Their mothers, often victims of abuse, sometimes lack the resources to reenter society.

Research by myself and others has shown that "houselessness" is only one aspect of homelessness. Home implies basic shelter, but it also entails connection to a community of supports, including friends and family, organizations that share common values and beliefs, such as churches, as well as caretaking institutions. Homelessness marks a rupture in community and family ties in addition to a loss of residence.

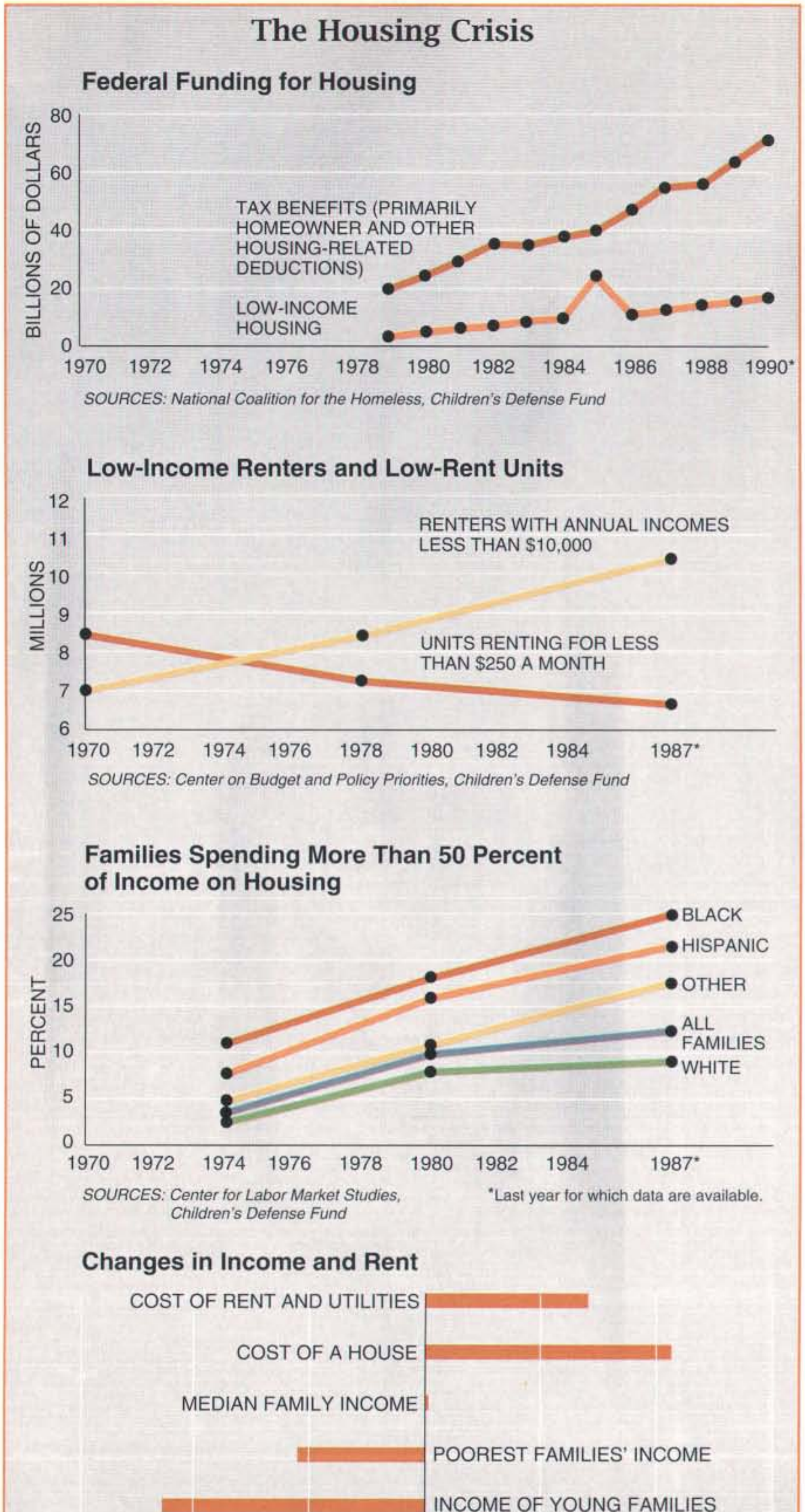
By examining the plight of homeless mothers and children, we can begin to understand the far-reaching societal impact of their situation. And by delineating the many factors leading to homelessness, we can suggest long-term policy decisions that realistically address the diverse needs of these families.

ELLEN L. BASSUK is president of The Better Homes Foundation, a nonprofit organization serving homeless families, and associate professor of psychiatry at Harvard Medical School. She has done extensive clinical research in the areas of emergency psychiatry, mental illness and homelessness and has conducted pioneering studies on the effects of homelessness on children. Bassuk received her B.A. from Brandeis and her M.D. from Tufts University.

Roots of family homelessness are myriad and apply to discussions of homeless adult individuals, runaway youths as well as parents with children. During the past decade, cutbacks in benefits coupled with severe shortages of low-income housing jeopardized the stability of all people with reduced or fixed incomes—pushing many onto the streets. Although the size of the homeless population is unknown, experts agree it is growing. An advocacy group, the Partnership for the Homeless reported that the number of homeless people increased 18 percent between 1988 and 1989. Estimates of the numbers of homeless vary wildly according to the source, design and agenda of the study: from 250,000 to as many as three million nationwide.

Ironically, increases in social welfare spending, both in real dollars and in percent of gross national product, did not benefit the poor during the 1980s. Social security expenditures, for example, helped only the elderly. Even financial assistance programs, such as Aid to Families with Dependent Children (AFDC), accomplished little. Although

MOTHER AND CHILDREN live in a housing facility for homeless families. Such families now make up 34 percent of the homeless population, and their numbers are growing. Every night between 61,500 and 100,000 American children are homeless.



most homeless families receive such aid, the amounts are well below the 1990 federal poverty income level of $13,359 for a family of four. Indeed, the maximum amount of AFDC available to a family of three—even when taken together with food stamp benefits—bought 26 percent less in 1990 than it did in the early 1970s.

At the same time financial assistance plummeted for many persons, housing costs outdistanced income. The median rents of unsubsidized, low-income apartments climbed from $255 to $360. And the number of poor renters increased from 4.5 million in 1974 to seven million in 1987.

Gentrification and the conversion of apartments to condominiums further depleted the supply of affordable housing. This shortage was never addressed by the federal government. In the past 10 years the government virtually ceased funding construction or rehabilitation programs for low- and moderate-income housing. Between 1980 and 1987, new commitments for the construction of public and Section 8, or subsidized, housing fell from about 173,249 to 12,244 apartments, reports Michael A. Stegman of the University of North Carolina at Chapel Hill.

Dwindling aid and housing shortages are not problems specific to mothers and their children, but this group is particularly at risk. More women are running households than ever before in U.S. history. In 1970, for example, one in 10 families were headed by women, according to Senator Daniel Patrick Moynihan of New York, who has written a book on the subject; by 1989, more than one in five families were headed by women.

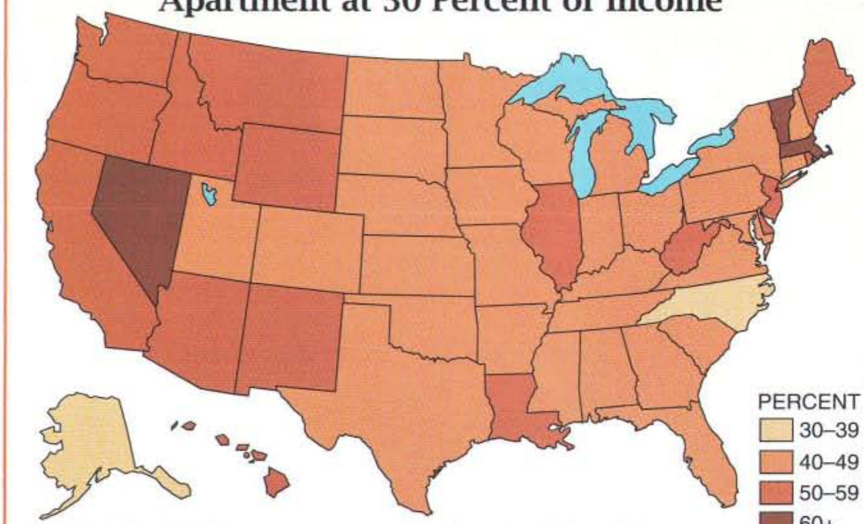
Approximately one third of the families headed by women are living below the poverty line, and studies by the Urban Institute have found that they are generally poorer than families of aged or disabled persons. Although the numbers of poor people and the overall poverty rate decreased slightly between 1983 and 1989, the poverty rate surged during 1990: 2.1 million more Americans became poor. Meanwhile the poverty rate among children and female-run households remained consistently high. The number of poor, female-run families grew 25.5 percent between 1970 and 1979 and another 15 percent between 1980 and 1989. The Census Bureau recently reported that children younger than 18 years make up 38 percent of the 33.6 million poor in the U.S.

Because homelessness is a manifestation of extreme poverty and because families headed by women are dispro-

portionately poor, these families are especially vulnerable to economic vicissitudes. The situation is exacerbated by today's housing market. Even if a mother is working full-time and has child care provided free by a family member, rent constitutes a large proportion of her budget. Any unexpected drop in income or rise in expenses may easily dislodge her and her family.

Furthermore, because many cities have low vacancy rates and because waiting lists for public housing are years long, families able to survive with little after-rent income are often unable to find housing. Housing vouchers are sometimes available, but supply cannot meet demand; mothers with more than three children are sometimes considered undesirable tenants.

U.S. Families Unable to Afford a Two-Bedroom Apartment at 30 Percent of Income



SOURCE: Cushing N. Dolbeare, Low-Income Housing Information Service, 1991

Economic dislocation alone cannot explain how one poor, female-run family manages to maintain a home while another must turn to an emergency shelter for refuge. Within the subset of such households are families particularly susceptible to homelessness. Research suggests that a lack of relationships and resources such as savings or child care can hamper a family's capacity to remain housed.

In a vicious cycle, the housing famine itself destroys some of these supports by dislocating entire families. Initially, some homeless families may live with friends or family, doubling up in already overcrowded living quarters. As time passes, such relationships tend to weaken. Indeed, most families move several times in a year before becoming homeless. Martha, for example, lived with her relatives and friends before she turned to abandoned buildings and shelters.

From the outset, however, many homeless mothers have never had people to turn to for help. In 1985 we conducted a study of the needs of 80 families and 151 children living in Massachusetts family shelters. We found that most mothers were disconnected not only from caretaking institutions—such as day care—but from friends and family.

The reasons for the isolation may stem from the mother's own childhood. Studies of homeless mothers have documented a relatively high frequency of early and current disruptive experiences, including divorce, desertion, illness, parental death or victimization. In a recent Boston University study, Lisa A. Goodman reported that 89 percent of homeless mothers had been the victims of physical or sexual abuse at some point in their lives, 67 percent while children.

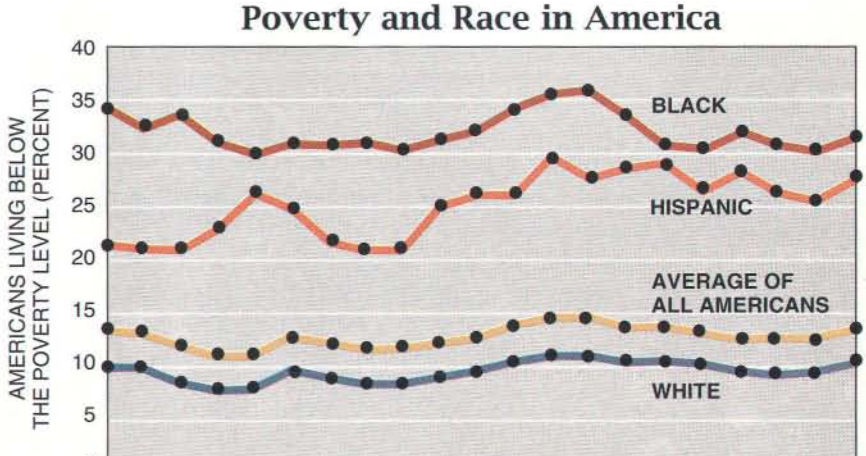
As a result of a traumatic childhood, some homeless mothers may never have had adequate supports or the capacity to find and keep them. Difficult early experiences can impede the development of social skills, hindering a person's ability to find employment and seek social services as well as to form sustaining long-term relationships.

The lack of social skills can thwart these women's efforts to maintain jobs. Research indicates that although most homeless mothers have completed two or three years of high school, they generally have limited work experience, which is compounded by sexual discrimination in the job market. Employment alone, however, does not guarantee financial security. Even if these women are employed in service-sector jobs, which pay the minimum wage of $4.25 per hour, many cannot make ends meet. Without job training and adequate child care, it is difficult to imagine how they could afford current rents or become self-sufficient.

Some homeless families are also hindered by substance abuse and mental illness. Although few systematic epidemiological studies have been completed, an estimated 10 to 30 percent of homeless mothers abuse alcohol or drugs such as crack cocaine. The use of drugs further complicates the situation of these families and sometimes impairs their ability to raise children. In contrast to single homeless adults, homeless mothers in family shelters have lower rates of chronic mental illness, particularly schizophrenia, and most have not become homeless as a result of deinstitutionalization.

The high incidence of pregnancy among these women may contribute to

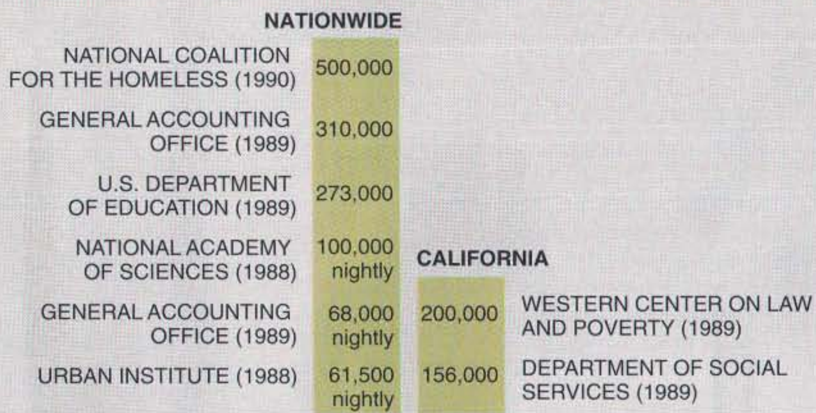
Poverty and Race in America



SOURCES: U.S. Census Bureau, New York Times

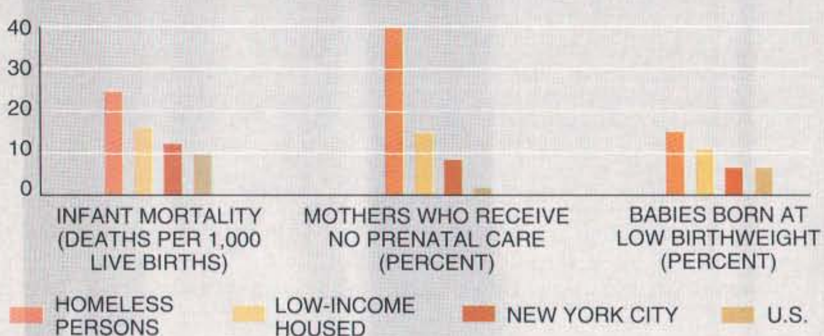
Children and Homelessness

Estimates of the Annual Number of Homeless Children



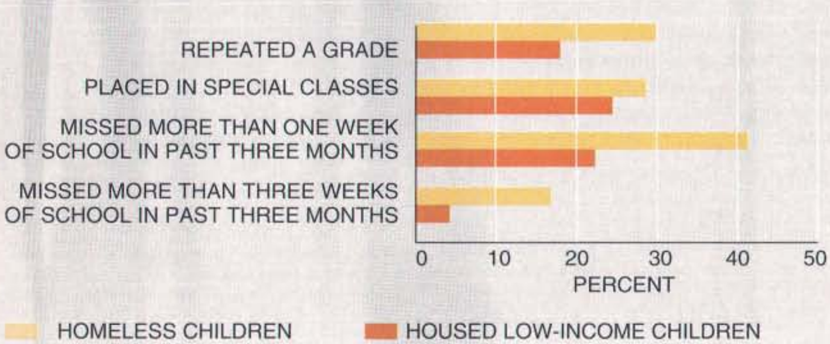
SOURCE: Children's Defense Fund

Homelessness and Child Health



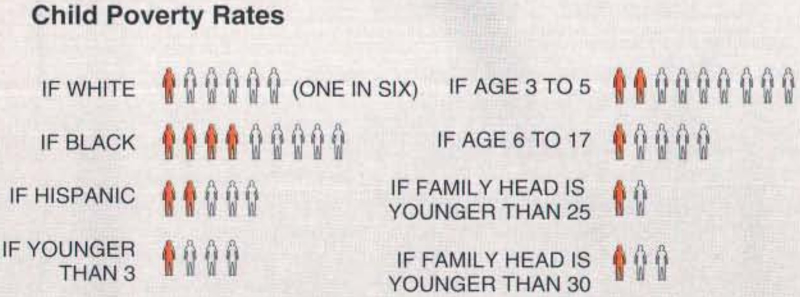
SOURCES: Wendy Chavkin, Columbia University, 1987; Children's Defense Fund

Homelessness and Education



SOURCES: David Wood, Cedars Sinai Medical Center, Los Angeles, 1989; Children's Defense Fund

Child Poverty Rates



SOURCE: Children's Defense Fund, 1989

homelessness. According to a 1989 New York City study by James R. Knickman and Beth C. Weitzman of New York University, pregnant women receiving AFDC had an 18 percent chance of becoming homeless as compared with a 2 percent chance for women who were not pregnant. Data from 17 cities suggest that the pregnancy rate among homeless women is 12 percent—other studies put the rate at 35 percent. The rate for the general population was 10.8 percent in 1985, the most recent year for which figures can be obtained.

Homeless women are frequently poorly nourished and receive little or no prenatal care. A 1987 report by the New York City Department of Health revealed that 40 percent of the homeless women studied had no prenatal care at all. Consequently, they are at high risk for adverse pregnancy outcomes and low-birthweight babies.

The problems of the mothers are in turn mirrored in their children—the cycle is perpetuated. The prevalence of alcohol and drug abuse among homeless women threatens the health of their babies. A 1989 report by the Select Committee on Children, Youth and Families found that the number of drug-exposed babies tripled or quadrupled in most surveyed hospitals between 1985 and 1988. Some of these infants manifest congenital abnormalities, mental retardation and long-term neurobehavioral problems.

Although foster care families take in some of these infants, the system is overburdened. One Miami hospital, for instance, has 20 to 30 boarder babies on any given day: a new Florida state law mandates that all drug-exposed newborns are wards of the state.

The select committee also reported a high correlation between substance abuse and child abuse and neglect—in all families, housed and homeless alike. In the District of Columbia, for example, substance abuse was implicated in more than 80 percent of the reported cases of child abuse.

Homeless children experience more acute and chronic medical problems than do poor children who have homes. Health care workers find high incidences of diarrhea and malnourishment, as well as asthma and elevated blood levels of lead in shelter children. The Children's Defense Fund reported that homeless children are three times more likely to have missed immunizations than are housed children.

The psychological well-being of homeless children is no better, as the case of 12-year-old Robert, living in a Boston shelter, illustrates. When interviewed,

Robert said he was ugly and often thought about killing himself and would do so if he had the chance. He was not sure how he would carry out this intent but said he felt desperate enough to hold it as an idea.

Robert said he hated school. He stated that he had no friends and was bored and that he worried his classmates would discover he had no real home. Robert said he was teased by his peers and criticized by adults. He disliked the shelter and the other children there and spoke wistfully of the family's last home in a trailer. Robert was failing in school and had repeated a grade.

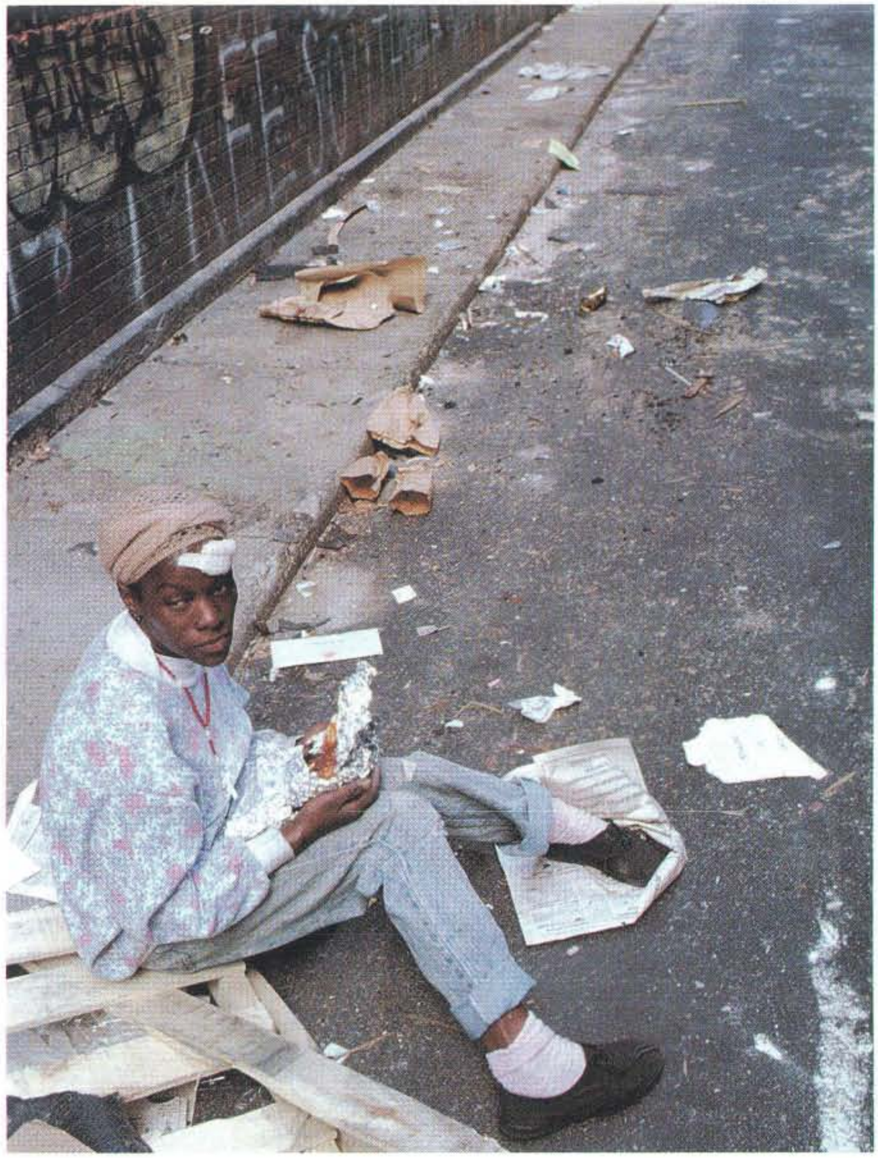
In our 1985 study we discovered that almost half of the homeless preschoolers manifested serious emotional and developmental delays. When compared with poor, housed children, homeless children were slower in language development, motor skills, fine-motor coordination and personal and social ability. Studies from Los Angeles, New York City, St. Louis and Philadelphia have subsequently reported similar findings.

A 1989 Department of Education report estimated that 30 percent of the nation's 220,000 school-age homeless children do not attend school regularly. The National Coalition for the Homeless, an advocacy group, estimates that the actual numbers of homeless school-age children are two to three times as great and that as many as 50 percent are not attending school.

As homeless children move from place to place, and switch from school to school, they are likely to become victims of bureaucracy. The sluggish transfer of academic records or files can delay their enrollment and set them back further. In addition, the lack of subsidized transportation and child care threatens their mothers' ability to get them to school and back to the shelter.

Many homeless children who do attend school, such as Robert, are failing or doing below-average work. The few studies conducted on this problem found that between 30 and 50 percent of homeless children had repeated a grade. In New York City most homeless children scored below grade level in mathematics and reading.

Because some homeless children fall behind their peers, they may be designated as having special needs. When this is the case, an educational plan must be formulated to address the child's unique problems, and, whenever possible, access must be provided to special educational services. In the nation's underfunded public school system, however, these resources are not often available. It is unlikely that the parent alone will be able to help their child catch up. Thus, many children remain behind and are at high risk of becoming dropouts. Although the precise figure is not known, the dropout rate for homeless children is suspected to be much higher than the nation's already elevated rate of 28.6 percent.



YOUNG WOMAN lives on the streets of New York City while her child stays with her mother. Such women are particularly vulnerable to street violence.

Although there are no easy solutions to the plight of homeless families, the crisis-oriented policies of the past decade have clearly failed. One facet of this policy is the emergency shelter system. Homelessness has been incorrectly viewed as a transient response to a situational crisis, that is, a temporary lack of low-income housing or employment. The shelter system was predicated on this erroneous assumption, yet these emergency facilities are becoming institutionalized. The Department of Housing and Urban Development (HUD) counted 1,900 shelters in 1984; by 1988, there were 5,400 shelters. During these four years, the percentage of sheltered families rose from 21 to 40.

Even some facilities better designed to meet the complex needs of homeless families are an incomplete solution. So-called transitional services provide longer lengths of stay as well as a combination of housing assistance, education, job training, psychosocial help and health care. In many ways, the structured, supervised environment of these facilities is best suited to helping families in crisis as well as those who are particularly troubled. These expensive, interim facilities, however, necessitate a move to permanent housing.

At present the high volume of clients

for both emergency shelters and transitional housing often leads to an unfortunate paradox. Forced to choose, the staff of these residences often exclude families with problems such as substance abuse, family violence and physical or mental disabilities. The overflow of clients is sometimes placed in welfare hotels, where there are few services. Even mothers leaving transitional facilities are infrequently monitored or followed by caseworkers. Facing their troubles alone again, these mothers can easily fall prey to the same situation that first led them to homelessness. In both cases, those mothers and children most in need of help are often least likely to find it.

The federal government's efforts to provide housing that goes beyond emergency shelter or transitional facilities to offer more complete services have been minimal. In 1987 the passage of the Stewart B. McKinney Act (the Homeless Assistance Act) offered new hope with the designation of $490.2 million for aid to the homeless. An additional $1.2 billion was appropriated over the next three years. The money was spent on supportive housing, residential programs, health and mental health care, education for children and job training for all homeless people. Although the McKinney Act was a promising first step, the funds were spread too thin and were not directed to supplying permanent housing or long-term services.

Indeed, for the most part, the federal government has proved unwilling to combat homelessness. Consequently, states, cities and private nonprofit organizations have been left with an enormous, often impossible, task. New York City, for instance, just announced the failure of its plan for homeless families. The more than $25-million, year-old "Alternative Pathways" program, designed to prevent the eviction of 10,000 families and to pay the unpaid rent of 32,000 families, was understaffed and underfunded. As a result of its failure, an anticipated 6,000 families will be living in shelters by June 1992—more than ever before in the city's history.

To address realistically homelessness and its parent, extreme poverty, the nation needs to rethink its policy completely. First, citizens must elect representatives who allocate adequate funds for domestic needs: housing, a higher minimum wage, education, health care, child care and social services. Such spending will assist both homeless families and those living in poverty. Ultimately, it will prevent many instances of homelessness.

Second, comprehensive programs for homeless persons must be made available and must be integrated with permanent housing. This situation fosters community ties and offers families autonomy while providing the services they need. One model of such an approach is a joint effort started in 1989 by the Robert Wood Johnson Foundation and HUD. Under the Homeless Families Program, nine cities, including Atlanta, Baltimore and Denver, will receive a projected $600,000 grant each over five years to implement services for homeless families. The program also makes available 1,200 Section 8 certificates, public housing assistance funds, worth about $35 million over five years.

In each city, parents and children are housed in residences that are clustered so that the families can provide support for one another. Families are followed by case managers who ensure that mothers receive appropriate treatment for mental health or substance abuse problems—one program provides testing for HIV infection. Employment training and child care are also made available. To date, the initiative has helped more than 100 homeless families move from emergency shelters to permanent housing.

The Better Homes Foundation, which I co-founded, supports similar efforts. Since its inception in 1988, the foundation has awarded $1.7 million to 55 programs that provide a range of services, including prenatal and pediatric health care, housing and entitlements assistance, substance abuse programs, parenting services and long-term case management.

The foundation also collaborates with other organizations. In a joint venture with IBM, for example, the foundation established the Kidstart program. Case managers assess the social, emotional and cognitive development of homeless preschoolers. They then help children gain access to programs such as Headstart, a federally funded educational service; they provide counseling and help homeless mothers with their parenting responsibilities. The Kidstart model is particularly effective because many homeless children have special needs and are therefore entitled by law to receive appropriate services. By negotiating bureaucracy and helping parents, case managers can protect children from some of the disastrous effects of homelessness.

Unfortunately, such programs are available only to a small number of homeless families. Before comprehensive programs can be widely implemented, a perceptual change must occur among policymakers and the general public. The fact that most homeless families are extremely poor and that a significant subgroup have other vulnerabilities as well has contributed to an ideological tension and prejudice ever present below the surface of American politics. Before effective solutions can be achieved, we must eradicate biases against homeless people.

In the early 1980s a largely economic explanation of homelessness was pit-

The Economy of Intervention

PRENATAL CARE FOR A PREGNANT WOMAN FOR NINE MONTHS	$600
MEDICAL CARE FOR A PREMATURE BABY FOR ONE DAY	$2,500
A SMALL CHILD'S NUTRITIOUS DIET FOR ONE YEAR	$842
SPECIAL EDUCATION FOR A CHILD WITH A MILD LEARNING DISABILITY FOR ONE YEAR	$4,000
A MEASLES SHOT	$8
HOSPITALIZATION FOR A CHILD WITH MEASLES	$5,000
DRUG TREATMENT FOR AN ADDICTED MOTHER FOR NINE MONTHS	$5,000
MEDICAL CARE FOR A DRUG-EXPOSED BABY FOR 20 DAYS	$30,000
SCHOOL-BASED SEX EDUCATION PER PUPIL FOR ONE YEAR	$135
PUBLIC ASSISTANCE FOR A TEENAGE PARENT'S CHILD FOR 20 YEARS	$50,000
SIX WEEKS OF SUPPORT SERVICES SO PARENTS AND CHILDREN STAY TOGETHER	$2,000
FOSTER CARE FOR A CHILD FOR 18 MONTHS	$10,000

SOURCES: State Office for Children, Children's Defense Fund, U.S. Department of Agriculture, Time Magazine, 1990

ted against one that focused on individual frailties. One side believed homeless people were economically dislocated by a system that concentrated the wealth among a small class of highly privileged citizens. The other side asserted that the homeless were chronically disabled by various social pathologies. At its most extreme, this view was expressed by President Ronald Reagan: "Some of those people are there, you might say, by their own choice."

The debate was fueled by data showing that homeless families, not unlike poor families, suffer disproportionately from substance abuse and mental disorders. Researchers, such as myself, studying these problems were accused of stigmatizing an already disenfranchised population—of blaming the victim. In an effort to protect the homeless, some advocates and providers refused to acknowledge mental illness or substance abuse. They simply concluded that permanent housing would eliminate homelessness.

Rather than employing new data that chronicled the complexities of homelessness, some advocates and critics tended simplistically to ascribe homelessness to single factors. When they identified a problem such as mental illness, for example, they interpreted the studies as indicative of one-to-one causality—with no regard to the context of extreme poverty. Along these lines, various editorials even concluded that homelessness was not a housing problem and that the homeless merely needed to be institutionalized.

MOTHER AND SON stand outside the Human Resources Administration in New York City, where they applied for housing. They are living in a shelter.

At the heart of this debate are society's views of economic misfortune, individual frailties and personal disabilities. Traditionally, emotional and social problems have been judged as the moral shortcomings of an individual. Someone suffering from a psychiatric illness or an addiction is rarely viewed as a person who has a disorder or who is taxed by overwhelming circumstances. Instead the affliction becomes a metaphor for a host of evils; it serves as testimony of the individual's unworthiness, a cause for condemnation.

Unless a multidimensional understanding of the origins of homelessness is reached along with acknowledgment of the heterogeneity of homeless family needs, we will continue to formulate ineffective policies. We must recognize that families on the street need more than just shelter. They need employment, a community, sustaining relationships, health care, child care and education.

The serious systemic ills plaguing this country virtually ensure homelessness for a growing number of families. Until the federal government provides ample housing, welfare and employment, vulnerable families will continue to struggle. Although we know the direction we must take to ameliorate extreme poverty and homelessness, our unwillingness to do so reflects our values and our priorities. The debate about the origins of homelessness has diverted attention away from the most basic issue: Are we willing to care for the most disenfranchised among us, whether it be on the basis of economic need or individual need, or both? Are we willing to lose another generation of young women and children?

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Quantum Cosmology and the Creation of the Universe

By applying quantum mechanics to the universe as a whole, cosmologists hope to look beyond the very instant of creation

by Jonathan J. Halliwell

Many of us have stared out into space on a clear night and wondered, "Where did all this come from?" For many centuries, this question, pondered by philosophers and theologians, lay far outside the reach of scientific investigation. Only in this century has theory grown sufficiently subtle and rigorous to provide a plausible look at the very beginning of the universe. Using Einstein's theory of general relativity to extrapolate back in time, investigators deduced that the universe emerged from a single, unbelievably small, dense, hot region. The events that have unfolded since that moment, including the formation of matter as well as its coalescence into galaxies, stars, planets and chemical systems, appear to be adequately described by conventional cosmology.

Yet the conventional ideas are incomplete. They fail to explain or even describe the ultimate origin of the universe. The most extreme extrapolation backward in time takes the universe down to a size at which it is necessary to incorporate that other great vision of modern physics: quantum theory. But the marriage of quantum theory and general relativity has been described as, at best, a shotgun wedding. Its consummation remains one of the outstanding problems of physics.

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In recent decades, workers have begun to make some progress in applying quantum theory to the universe. These early steps have been promising enough to encourage those taking them to coin a name for their endeavor: quantum cosmology. Quantum cosmologists build on foundations laid in the 1960s by Bryce S. DeWitt of the University of Texas at Austin, Charles W. Misner of the University of Maryland and John A. Wheeler of Princeton University. Their studies mapped out how quantum mechanics might be applied to the entire universe. But the work was not taken very seriously until the 1980s, after classical theories of cosmology began to falter in their attempts to explain fully the beginning of the universe.

Most notable among the investigators who were drawn to this work are James B. Hartle of the University of California at Santa Barbara, Stephen W. Hawking of the University of Cambridge, Andrei D. Linde of the Lebedev Physical Institute in Moscow and Alexander Vilenkin of Tufts University. They put forward quite definite laws of initial conditions, that is, conditions that must have existed at the very moment of creation. When adjoined with suitable laws governing the evolution of the universe, such proposals could conceivably lead to a complete explanation of all cosmological observations and would therefore resolve important problems that plague the foundations of conventional cosmology.

Central to the conventional scenario is the hot big bang model of the universe. Since George Gamow first proposed it in 1948, the idea of an explosive birth has steadily and successfully battled other theories concerning the origin of the universe. Other researchers have over the intervening decades refined the model. Using general relativity and some basic physical laws, the model as it exists today envisages a beginning from an extremely small, hot, dense initial state some 15 billion years ago. The universe subsequently expanded, developing into the large, cold universe that we observe today.

The hot big bang model makes definite predictions about the universe as it exists now. It predicts the formation of nuclei, the relative abundances of certain elements and the existence and exact temperature of the microwave background—the glow of radiation left over from the initial explosion, which permeates the universe. The prediction of the cosmic background radiation, made by Ralph A. Alpher of Union College and Robert Herman of the University of Texas at Austin, was confirmed by Arno A. Penzias and Robert W. Wilson of Bell Laboratories in 1964.

Despite its successes, the hot big bang model leaves many features of the universe unexplained. For example, the universe today includes a vast number of regions that in the hot big bang model could never have been in causal contact at any stage in their entire history. These regions are moving away from one another at such a rate that any information, even traveling at the speed of light, could not cover the distance between them. This "horizon problem" makes it difficult to account for the striking uniformity of the cosmic background radiation.

Then there is the "flatness problem." The hot big bang model indicates the

GALAXY CLUSTER Abell 1060 contains many spirals and ellipticals. The emergence of galaxies is one of the celestial features classical cosmology fails to explain fully. Quantum cosmology may provide the missing concepts.

universe to become more curved as time passes. But observations reveal that the spatial geometry of the part of the universe we can observe is extremely flat. The universe could exhibit such flatness only if it started out almost exactly flat—to within one part in 10^{60}. Many cosmologists consider such fine-tuning deeply unnatural.

Perhaps most significant, the hot big bang model does not adequately explain the origin of large-scale structures, such as galaxies. Researchers, among them Edward R. Harrison of the University of Massachusetts at Amherst and Yakov B. Zel'dovich of the Institute of Physical Problems in Moscow, offered partial explanations, showing how large-scale structures might appear from small fluctuations in the density of matter in an otherwise homogeneous early universe. But the fundamental origin of these fluctuations remained completely unknown. They had to be assumed as initial conditions.

In brief, therefore, the hot big bang model suffered from extreme dependence on initial conditions. Finding the present universe in this model would be as unlikely as finding a pencil balanced on its point after an earthquake.

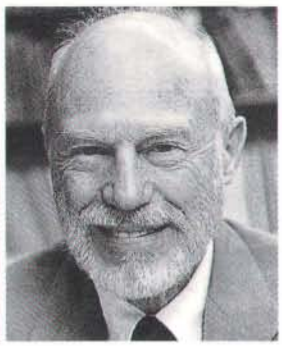
In 1980 Alan H. Guth of the Massachusetts Institute of Technology proposed a compelling alternative to excessive fine-tuning. His model, known as the inflationary universe scenario, resembles the hot big bang except for one essential difference: Guth's scheme holds that the universe began with a very brief but exceedingly rapid period of expansion. This process, called inflation, would have lasted for an unbelievably fleeting moment—some 10^{-30} second. During this time, the universe would have increased in size by an equally astounding factor of 10^{30}, growing from an initial size of 10^{-28} centimeter to about one meter [see "The Inflationary Universe," by Alan H. Guth and Paul J. Steinhardt; SCIENTIFIC AMERICAN, May 1984].

Guth's inflation is essentially an incredibly brief glitch inserted into the beginning of the hot big bang model. But it is sufficient to solve many of the problems. Inflation solves the horizon problem because the observed universe emerges from a region small enough to permit causal contact. The flatness problem vanishes because the huge expansion blows the universe up so much that it appears flat—much as any specific area on the surface of a large,

Some Contributors to Modern Cosmology

ERWIN SCHRÖDINGER (1887–1961), an Austrian physicist, was one of the fathers of quantum mechanics. Using the idea that matter may behave as a particle or wave, he established the fundamental equation that determines the wave function for atomic systems. Intellectually versatile, he later studied the philosophy and literature of Western cultures and attempted to show how quantum physics could be used to explain genetic structure.

GEORGE GAMOW (1904–1968) emigrated from the U.S.S.R. in 1934. A volatile and prolific contributor to many areas of physics, he put forward the idea of the big bang in 1948 as part of a theory of the origin of light elements. Brilliant, but considered eccentric by some of his peers, he was not always taken very seriously.



JOHN A. WHEELER (b. 1911), now emeritus professor at Princeton University, has made major contributions to many theories of modern physics, from a quantum description of nuclear fission to neutron stars and black holes. He studies the philosophical implications of quantum mechanics as well.

BRYCE S. DEWITT (b. 1923) of the University of Texas at Austin has worked on theories of applying quantum theory to the universe and of quantum gravity. Together Wheeler and DeWitt formulated the cosmological analogue to the Schrödinger equation in the 1960s.

inflated balloon will appear flat. The density-fluctuation problem is also solved; the scenario predicts that the sudden expansion would have locked in quantum fluctuations that could have seeded the formation of large-scale structures.

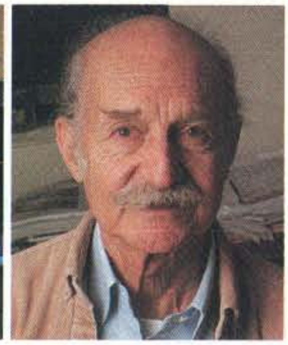
But why would such a moment of inflation happen? Guth found a plausible cause in the form of a particular kind of matter. In the hot big bang model, the matter content of the universe is a uniformly distributed plasma or dust. Guth's model considers matter to consist of scalar-field particles. Such field particles are not the stuff of everyday life, but they do arise naturally in many theories. Indeed, they are believed to be the dominant form of matter under the extremely high energy conditions similar to those in the early universe. According to the inflationary model, they lead to a kind of negative pressure. Gravity effectively becomes a repulsive force, and inflation occurs. At the end of the inflationary era, the decay of the scalar-field matter producing the expansion heated the (initially cold) universe to a very high temperature. The subsequent evolution exactly follows the path described by the hot big bang model: the universe expanded and cooled, and the residual heat is detectable as the cosmic background radiation.

Perhaps the most important aspect of the inflationary universe scenario is that, as mentioned above, it provides a possible explanation for the origin of the density fluctuations that would have seeded galaxies and other structures. The inflationary universe scenario assumes that although the scalar field is largely homogeneous, it still may have small, inhomogeneous parts. According to quantum theory, these inhomogeneous parts cannot be exactly zero but must be subject to small quantum fluctuations. (In fact, all types of matter are subject to such quantum effects, but for most purposes the fluctuations are so small as to be totally insignificant.) The rapid expansion of the universe during inflation magnified these initially insignificant microscopic fluctuations, transforming them into macroscopic changes in density. (The much slower expansion in the hot big bang model is incapable of producing this effect.) Indeed, detailed calculations showed that, subject to certain assumptions about the scalar field, the resultant density fluctuations were of the type suggested by Harrison and Zel'dovich.

Inflation improves dramatically on the hot big bang model in that it allows for the currently observed state of the universe to have arisen from a much broader, far more plausible set of initial conditions. Nevertheless, inflation does not relieve the observed state of the universe of all dependence on assumptions about initial conditions. In particular, inflation itself depends on a number of assumptions. For example, it would have occurred only if the scalar field began with a large, approximately constant energy density. This approximately constant energy density is equivalent, at least for a brief time, to Einstein's famous (or infamous) cosmological constant. Therefore, like it or not, the success of inflation rests on certain assumptions about initial conditions.

From where do these assumptions come? Obviously, one can go on asking an infinite sequence of such questions, like an overbearingly curious child in the "Why?" stage. But the cosmologist seeking a complete explanation is ultimately compelled to ask, "What happened before inflation? How did the universe actually begin?"

One can start answering these questions by following the expansion of the universe backward in time to the preinflation era. There the size of the universe tends to zero, and the strength of the gravitational field and the energy density of matter tend to infinity. That is, the universe appears to have emerged from a singularity, a region of infinite curvature and energy density at which the known laws of physics break down.



RALPH A. ALPHER (b. 1921), a protégé of Gamow now at Union College, and **ROBERT HERMAN** (b. 1914) of the University of Texas at Austin, predicted the existence of the cosmic background radiation while at Johns Hopkins University in 1948, as they worked to make consistent the Russian physicist's theories concerning the birth of the universe and the creation of the light elements.

HUGH EVERETT III (1930–1982), a student of Wheeler in the 1950s at Princeton, solved the observer-observed problem with his "many worlds" interpretation, which was originally developed as his Ph.D. thesis. Later, he became a defense analyst and contributed to game theory and operations research.

STEPHEN W. HAWKING (b. 1942) helped prove that singularities are an inescapable consequence of Einstein's general relativity. He is perhaps best known for demonstrating that black holes are not in fact black but radiate energy. He was instrumental in reviving quantum cosmology in the1980s, using it to understand what happened "before" the big bang. He holds Isaac Newton's chair at the University of Cambridge.

Singularities are not artifacts of the models. These conditions are a consequence of the famous "singularity theorems," proved in the 1960s by Hawking and Roger Penrose of the University of Oxford. These theorems showed that under reasonable assumptions any model of the expanding universe extrapolated backward in time will encounter an initial singularity.

The theorems do not imply, however, that a singularity will physically occur. Rather the theory predicting them—classical general relativity—breaks down at very high curvatures and must be superseded by some bigger, better, more powerful theory. What is this theory? A consideration of scale yields a clue. Near a singularity, space-time becomes highly curved; its volume shrinks to very small dimensions. Under such circumstances, one must appeal to the theory of the very small—that is, to quantum theory.

Quantum theory arose from an attempt to explain phenomena that lay beyond the scope of conventional classical physics. A central failure of classical mechanics was its inability to account for the structure of the atom. Experiments suggested that the atom consisted of electrons orbiting a nucleus, much as planets orbit the sun. Efforts to describe this model using classical physics, however, predicted that the electrons should plunge into the nucleus. There was nothing to hold them in orbit.

To overcome the discrepancy between observation and theory, Niels Bohr, Erwin Schrödinger, Werner K. Heisenberg and Paul A. M. Dirac, among others, in the early 20th century developed quantum mechanics. In this formulation, motion is not deterministic (as in classical mechanics) but probabilistic. The dynamic variables of classical mechanics, such as position and momentum, do not in general have definite values in quantum mechanics, which regards a system as fundamentally wavelike in nature. A quantity called the wave function encodes the probabilistic information about such variables as position, momentum and energy. One finds the wave function for a system by solving an equation called the Schrödinger equation.

For a single-point particle, one can regard the wave function as an oscillating field spread throughout physical space. At each point in space, the function has an amplitude and a wavelength. The square of the amplitude is proportional to the probability of finding the particle at that position. For wave functions that have constant amplitudes, the wavelength is related to the momentum of the particle. But because the wave functions for position and momentum are mutually exclusive, an indefiniteness, or uncertainty, in both quantities will always exist. As the measurement of one property, say, position, becomes more precise, the value for the other grows correspondingly indefinite. This state of affairs, called Heisenberg's uncertainty principle, is an elementary consequence of the wavelike nature of particles.

The uncertainty principle leads to phenomena qualitatively different from those exhibited in classical mechanics. In quantum mechanics, a system can never have an energy of exactly zero. The total energy is generally the sum of the kinetic and potential energies. The kinetic energy depends on momentum; potential energy depends on position (a ball on top of a hill has more gravitational potential energy than one that sits in a well). Because the uncertainty principle forbids any simultaneous, definite values of momentum and position, the kinetic and potential energy cannot both be exactly zero.

Instead the system has a ground state in which the energy is as low as it can be. (Recall that in the inflationary universe scenario, galaxies form from "ground-state fluctuations.") Such fluctuations also prevent the orbiting electron from crashing into the nucleus. The electrons have an orbit of mini-

mum energy from which they cannot fall into the nucleus without violating the uncertainty principle.

Uncertainty also leads to the phenomenon of tunneling. In classical mechanics, a particle traveling with fixed energy cannot penetrate an energy barrier. A ball at rest in a bowl will never be able to get out. In quantum mechanics, position is not sharply defined but is spread over a (typically infinite) range. As a result, there is a definite probability that the particle will be found on the other side of the barrier. One says that the particle can "tunnel" through the barrier.

The tunneling process should not be thought of as occurring in real time. In a certain well-defined mathematical sense, the particle is conveniently thought of as penetrating the barrier in "imaginary" time, that is, time multiplied by the square root of minus one. (Time here loses its meaning in the usual sense of the word; it actually resembles a spatial dimension more than it does real time.)

These distinctly quantum effects do not contradict classical mechanics. Rather quantum mechanics is a broader theory and supersedes classical mechanics as the correct description of nature. On macroscopic scales, the wavelike nature of particles is highly suppressed, so that quantum mechanics reproduces the effects of classical mechanics to a high degree of precision (although how this "quantum to classical" transition comes about is still a matter of current research).

How can these insights be employed to illuminate questions of cosmology? Like quantum mechanics, quantum cosmology attempts to describe a system fundamentally in terms of its wave function. One can find the wave function of the universe by solving an equation called the Wheeler-DeWitt equation, which is the cosmological analogue of the Schrödinger equation. In the simplest cases, the spatial size of the universe is the analogue of position, and the rate of the universe's expansion represents the momentum.

Yet many conceptual and technical difficulties arise in quantum cosmology above and beyond those in quantum mechanics. The most serious is the lack of a complete, manageable quantum theory of gravity. Three of the four fundamental forces of nature—electromagnetism, the strong nuclear force and the weak nuclear force—have been made consistent with quantum theory. But all attempts to quantize Einstein's general relativity have met with failure. The failure looms large: recall that general relativity, the best theory of gravity that we have, says that at the singularity, space becomes infinitely small and the energy density infinitely great. To look beyond such a moment requires a quantum theory of gravity.

I should note that proponents of a theory of "superstrings" claim it to be a consistent, unified quantum theory of all four forces of nature and thus is, or at least contains, a quantum description of gravity. Final judgment on superstring theory has not yet been passed. In any case, it is far from being a manageable theory directly useful to cosmology.

Another question that workers confront is the applicability of quantum mechanics to the entire universe. Quantum mechanics was developed to describe atomic-scale phenomena. The beautiful agreement between quantum mechanics and experiment is one of the great triumphs of modern physics; no physicist in his or her right mind harbors any doubts as to its correctness on the atomic scale. But a few may raise dissenting voices if one suggests that quantum mechanics is equally applicable to, say, tables and chairs.

The challenge is not easy to dismiss, because on the macroscopic scale the predictions of quantum mechanics coincide closely with those of classical mechanics. Genuine macroscopic quantum effects are extremely difficult to detect experimentally. Even more contentious is the most extravagant extrapolation possible: that quantum mechanics applies to the entire universe at all times and to everything in it. Acceptable or not, this is the fundamental assertion of quantum cosmology.

Another, perhaps more difficult issue concerns the interpretation of quantum mechanics applied to cosmology. In the development of quantum mechanics (as applied to atoms), it proved necessary to understand how the mathematics of the theory translates into what one would actually observe during a measurement. Bohr laid the foundations of this translation, known as quantum measurement theory, in the 1920s and 1930s. He assumed that the world may be divided into two parts: microscopic systems (such as atoms), governed purely by quantum mechanics, and external macroscopic systems (such as observers and their measuring apparata), governed by classical mechanics. A measurement is an interaction between the observer and the microscopic system that leads to a permanent recording of the event.

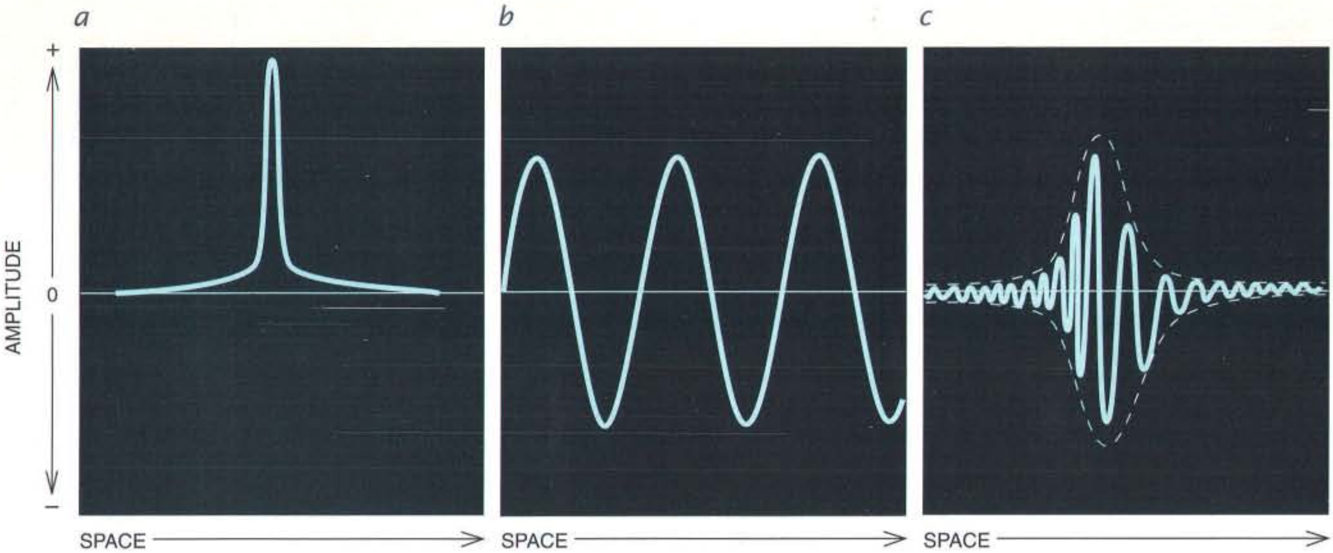
During this interaction, the wave function describing the microscopic system undergoes a discontinuous change from its initial state to some final one. The quantity being measured takes on a definite value in the final state. The discontinuous change is referred to, rather dramatically, as the collapse of the wave function. For instance, the wave function could start out in a state of definite momentum, but if position is being measured, it "collapses" into a state of definite position.

Although many theorists feel this scheme, known as the Copenhagen interpretation of quantum mechanics, is philosophically unsatisfactory, it nonetheless enables predictions to be extracted from theory—predictions that agree with observation. Perhaps for this reason, the Copenhagen interpretation has stood largely unchallenged for almost half a century.

In attempting to apply quantum mechanics to the entire universe, however, one meets with acute difficulties that cannot be brushed off as philosophical niceties. In a theory of the universe, of which the observer is a part, there should be no fundamental division between observer and observed. Moreover, most researchers feel uncomfortable at the thought of the wave function of the entire universe collapsing when an observation is made. Questions concerning probability predictions also come up. Ordinarily, one tests such predictions by making a large number of measurements. For example, flipping a coin many times will verify that the probability of heads is one half. In cosmology, there is only one system, which is measured only once.

Keeping such difficulties in mind, Hugh Everett III of Princeton, one of the first physicists to take seriously the notion of applying quantum mechanics to the universe, presented a framework for the interpretation of quantum mechanics particularly suited to the special needs of cosmology. Unlike Bohr, Everett asserted that there exists a universal wave function describing both macroscopic observers and microscopic systems, with no fundamental division between them. A measurement is just an interaction between different parts of the entire universe, and the wave function should predict what one part of the system "sees" when it observes another.

Hence, there is no collapse of the wave function in Everett's picture, only a smooth evolution described by the Schrödinger equation for the entire system. But as he modeled the measurement process, Everett made a truly remarkable discovery: the measurement appears to cause the universe to



UNCERTAINTY PRINCIPLE prevents any exact determination of a particle's position and momentum. The wave function for a particle in a state of definite position will be sharply peaked about a point in space, but the uncertainty in momentum is very large (*a*). The wave function for a state of definite momentum has a specific wavelength and a constant amplitude throughout all space, but the particle's position is completely uncertain (*b*). A "coherent" state represents a compromise (*c*). There is indefiniteness in both position and momentum, but it is as small as the uncertainty principle allows.

"split" into sufficiently many copies of itself to take into account all possible outcomes of the measurement.

Theorists have hotly debated the reality of the multiple copies in Everett's uneconomical "many worlds" interpretation. Indeed, modern versions of Everett's idea, generated most notably by Murray Gell-Mann of the California Institute of Technology and Hartle, play down the many-worlds aspect of the theory. Instead their versions talk about "decoherent histories," which are possible histories for the universe to which probabilities may be assigned. For practical purposes, it does not matter whether one thinks of all or just one of them as actually happening. These ideas also have the great merit of eliminating the role of the observer and the need to collapse the wave function. And despite the controversy, such approaches give theorists some kind of framework within which to work.

Gell-Mann and Hartle also address the issue of probabilities for the universe. They insist that the only probabilities that have any meaning in quantum cosmology are a priori ones. These probabilities are close to one or zero, that is, definite yes-no predictions. Although most probabilistic predictions are not of this type, they can often be made so by suitably modifying the questions one asks. Unlike quantum mechanics, in which the goal is to determine probabilities for the possible outcomes of given observations, quantum cosmology seeks to determine those observations for which the theory gives probabilities close to zero or one.

This kind of approach has led to the following understanding: at certain points in space and time, typically (but not always) when the universe is large, the wave function for the universe indicates that the universe behaves classically to a high degree of precision. Classical space-time is then a prediction of the theory. Under these circumstances, moreover, the wave function provides probabilities for the set of possible classical behaviors of the universe.

On the other hand, certain regions, such as those close to classical singularities, exist in which no such prediction is possible. There the notions of space and time quite simply do not exist. There is just a "quantum fuzz," still describable by known laws of quantum physics but not by classical laws. Hence, in quantum cosmology, one no longer worries about trying to impose classical initial conditions on a region in which classical physics is not valid, such as near the initial singularity.

Still, the wave function of the universe described by the quantum theory of cosmology does not eliminate the need for assumed initial conditions. Instead the question of classical initial conditions—the assumptions of the inflation and big bang models—becomes one of quantum initial conditions: Of the many wave functions possible (the many solutions to the Wheeler-DeWitt equation), how is just one singled out?

The problem is best understood by contrasting the cosmological situation with that of the laboratory, to which most of science is directed. There a system has clearly defined temporal and spatial boundaries—the duration of the reaction, for instance, or the size of the beaker. At those boundaries, experimenters may control, or at least observe, the physical states. Using suitable laws of physics, they may be able to determine how the initial or boundary conditions evolve in space and time.

In cosmology the system under scrutiny is the entire universe. By definition, it has no exterior, no outside world, no "rest of the universe" to which one could appeal for boundary or initial conditions. Furthermore, it seems most unlikely that mathematical consistency alone will lead to a unique solution to the Wheeler-DeWitt equation, as DeWitt once suggested. Therefore, in much the same way that the theoretical physicist proposes laws to govern the evolution of physical systems, the inescapable task of the quantum cosmologist is to propose laws of initial or boundary conditions for the universe. In particular, Hartle and Hawking, Linde, and Vilenkin have made quite definite proposals that were intended to pick out a particular solution to the Wheeler-DeWitt equation, that is, to single out a unique wave function for the universe.

Hartle and Hawking's proposal defines a particular wave function of the universe using a rather elegant formulation of quantum mechanics originally developed in the 1940s by the late Richard P. Feynman of Caltech. The formulation is called the path integral or sum-over-histories method. In ordinary quantum mechanics, calculation of the

wave function involves performing a certain sum over a class of histories of the system. The histories end at the point in space and time at which one wishes to know the value of the wave function. To render the wave function unique, one specifies precisely the class of histories to be summed over. The specified class includes not only classical histories but all possible histories for the system.

Summing over histories is mathematically equivalent to solving the Schrödinger equation. But it provides a very different view of quantum mechanics that has proved extremely useful, both technically and conceptually. In particular, the sum-over-histories method readily generalizes to quantum cosmology. The wave function of the universe may be calculated by summing over some class of histories for the universe. The technique is equivalent to solving the Wheeler-DeWitt equation, as was demonstrated most generally in a recent paper by Hartle and me. The precise solution obtained depends on how the class of histories summed over is chosen.

One way to understand the choice made by Hartle and Hawking is to translate their mathematics into geometry. Imagine the spatial extent of the universe at a particular time as a closed loop of string lying in the horizontal plane. If the vertical axis represents time, then the loop changes in size as time passes (representing the expansion and contraction of the universe). Various possible histories of the universe therefore appear as tubes swept out by the loop as it evolves in time [*see illustration below*]. The final edge represents the universe today; the opposite end is the initial state (that is, the creation of the universe), to be specified by proposed boundary conditions. Some tubes might close off in a sharp way, like the point of a cone; others might simply end abruptly.

Hartle and Hawking proposed that one should consider only tubes whose initial end shrinks to zero in a smooth, regular way, forming a kind of a hemispherical cap. One therefore sums over geometries that have no boundary (except for the final end, which is open and corresponds to the present universe). Hence, Hartle and Hawking's idea is called the no-boundary proposal.

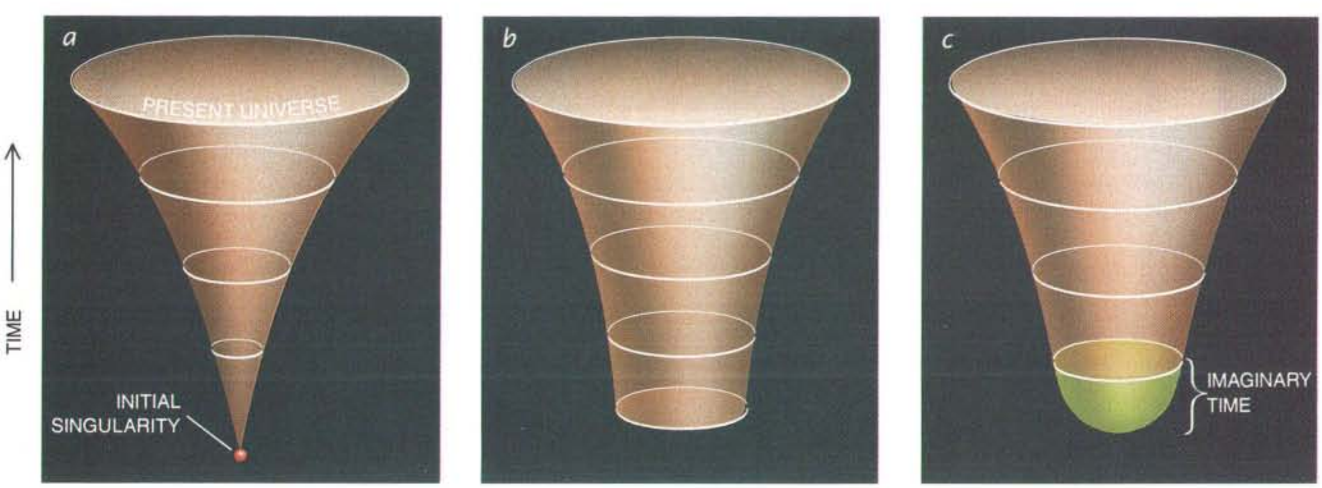
Closing off the geometry in such a smooth way is impossible in classical theory. The singularity theorems imply that the classical histories of the universe must shrink to zero in a singular way, much as the end of a cone shrinks to a point. But in quantum theory the sum-over-histories approach admits many possible histories, not just classical ones. The smooth closing off becomes possible. In particular, the region may be regarded as taking place in imaginary time and as such is distinctly nonclassical.

This reasoning has given rise to another proposal, or solution, to the Wheeler-DeWitt equation. Recall that the appearance of imaginary time is characteristic of tunneling processes in quantum theory. Perhaps, then, the universe has tunneled from "nothing." The evolution described by inflation and the big bang would have subsequently occurred after the tunneling. The no-boundary wave function, however, does not have the general features normally associated with tunneling. It gives high probability of a classical universe appearing with a large size and a low energy density. An ordinary tunneling process would suppress a transition from zero to large size and give highest probability for tunneling to small size that has a high energy density.

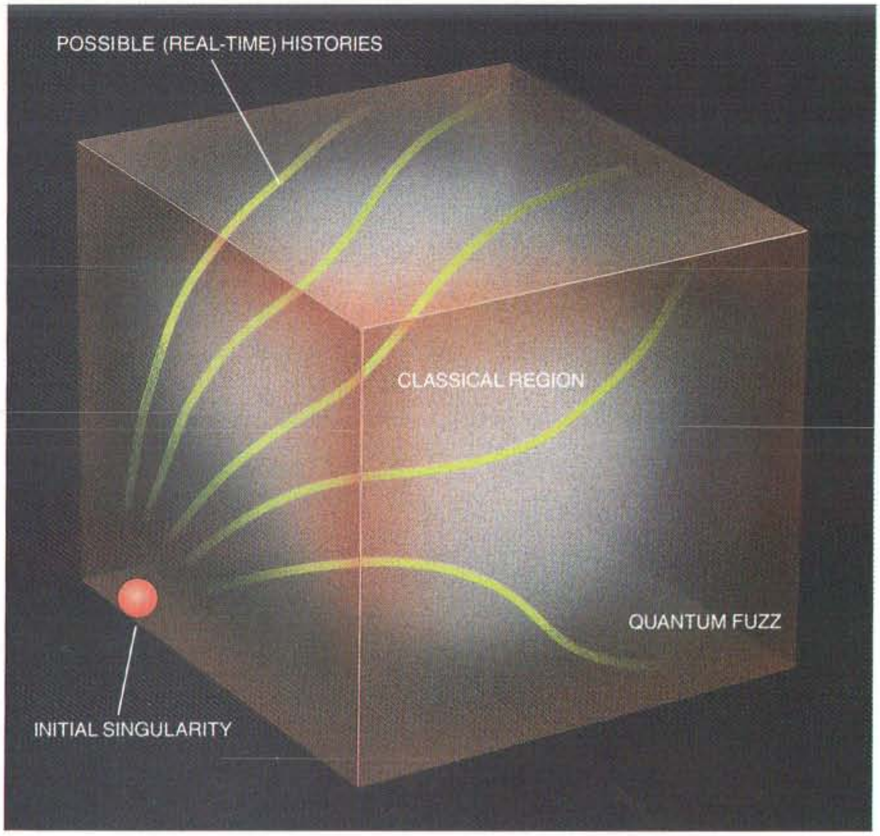
Partly for this reason, Linde and Vilenkin independently put forward a "tunneling" proposal. The precise statement of this idea is mathematical, but it suffices to say that the scheme is designed to pick out a solution to the Wheeler-DeWitt equation possessing the properties expected of a tunneling process. Their solution enables one to think more appropriately of the universe as tunneling from nothing.

The no-boundary and tunneling proposals select a unique wave function for the universe (contingent, however, on the resolution of a number of technical difficulties recently exposed by Hartle, Jorma Louko of the University of Alberta and me). In both, the wave function indicates that space-time behaves according to classical cosmology when the universe is a few thousand times larger than the size at which the four forces of nature would be unified (about 10^{-33} centimeter), in agreement with observation. When the universe is smaller, however, the wave function indicates that classical space-time does not exist.

Given a unique wave function of the universe, one may finally ask, "How did the universe actually begin?" Rather than answering, a quantum cosmologist would reframe the question. In the neighborhood of



SPACE-TIME "TUBES" can represent the evolution of the universe. In classical theories, any reasonable model of the universe encounters a singularity when evolved backward in time (*a*). In quantum cosmology the initial state of the universe may not necessarily be a point (*b*). Some specific proposals indicate that the universe began from a perfectly smooth kind of cap rather than a point (*c*). The "smoothing off" occurs in imaginary time, so it does not contradict singularity theorems, which refer to real time. Shortly after quantum creation, the universe evolved classically in real, physical time.



POSSIBLE HISTORIES of the universe, shown by the green lines, emerge from a "quantum fuzz," as indicated by the no-boundary and tunneling functions. The fuzz surrounds the (classically defined) initial singularity, but an observer looking back in time would see the histories emerge from a finite size in a nonsingular way.

singularities, the wave functions given by the tunneling and no-boundary proposals state that classical general relativity is not valid. Furthermore, the notions of space and time implicit in the question become inappropriate. The picture that emerges is of a universe with nonzero size and finite (rather than infinite) energy density appearing from a quantum fuzz.

After quantum creation, the wave function assigns probabilities to different evolutionary paths, one of which includes the inflation postulated by Guth. Although some theorists disagree, both the no-boundary and tunneling proposals seem to predict the conditions necessary for inflation, thereby eliminating the need for assumptions about the scalar-field matter that drove the rapid expansion.

The no-boundary and tunneling proposals also eliminate assumptions about the density perturbations. Although inflation explains their origin, the exact form and magnitude depend on certain assumptions about the initial state of the scalar-field matter. The inflation model assumes the inhomogeneous parts started out in their quantum mechanical ground state—the lowest possible energy state consistent with the uncertainty principle.

But in 1985 Hawking and I demonstrated this assumption must be a consequence of the no-boundary proposal: the correct kinds of inhomogeneities emerge naturally from the theory. The no-boundary proposal states that everything must be smooth and regular on the bottom cap of the space-time tube. This condition implies that inhomogeneous fluctuations must be zero there. Evolving up the tube in imaginary time, the fluctuations grow and enter the real-time region as small as they could possibly be—as the quantum mechanical ground-state fluctuations demanded by the inflation model. The tunneling proposal makes the same prediction, for similar reasons.

So we arrive at a possible answer. According to the picture afforded by quantum cosmology, the universe appeared from a quantum fuzz, tunneling into existence and thereafter evolving classically. The most compelling aspect of this picture is that the assumptions necessary for the inflationary universe scenario may be compressed into a single, simple boundary condition for the wave function of the universe.

How can one verify a law of initial conditions? An indirect test is to compare the predictions of the quantum models with the initial conditions needed for standard classical cosmological models. In this endeavor, as we have seen, quantum cosmologists can claim a reasonable degree of success.

More direct, observational tests are difficult. Much has happened in the universe since its birth, and each stage of evolution has to be modeled separately. It is difficult to distinguish between effects that result from a particular set of initial conditions and those that derive from the evolution of the universe or from the modeling of a particular stage.

What is needed is an observation of some effect that was produced at the beginning of the universe but was insensitive to the subsequent evolution. In 1987 Leonid Grishchuk of the Sternberg Astronomy Institute in Moscow argued that gravitational waves may be the sought-after effect. Quantum creation scenarios produce gravitational waves of a calculable form and magnitude. Gravitational waves interact very weakly with matter as they propagate through space-time. Therefore, when we observe them in the present universe, their spectrum may still contain the signature of quantum creation. Detecting gravitational waves is, unfortunately, extremely difficult, and current attempts have failed. New detectors to be built later this decade may prove sensitive enough to find the waves.

Because it is so hard to verify quantum cosmology, we cannot conclusively determine whether the no-boundary or the tunneling proposals are the correct ones for the wave function of the universe. It could be a very long time before we can tell if either is an answer to the question, "Where did all this come from?" Nevertheless, through quantum cosmology, we have at least been able to formulate and address the question in a meaningful—and most interesting—way.

FURTHER READING

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The Stem Cell

This master cell creates the key components of the human blood cell and immune systems. Isolating and manipulating the stem cell will lead to new treatments for cancer, immune defects and other disorders

by David W. Golde

Human blood contains a remarkable variety of cells, each precisely tailored to its own vital function. Erythrocytes, or red blood cells, transport life-sustaining oxygen throughout the body. Tiny platelets arrest bleeding by promoting clotting. White blood cells—which include lymphocytes, monocytes and neutrophils—form the immune system that guards an individual against attack by foreign tissue, viruses and various other microorganisms.

Amazing as it may seem, all these cells develop from a kind of master cell, the hematopoietic (blood-forming) stem cell, which resides primarily in the bone marrow. Injury to the stem cells—from chemotherapy, radiation or disease, for example—can cripple the immune and blood production systems. Transplanted bone marrow can be used to treat people whose stem cells have sustained such damage. In recent years, knowledge about the stem cell has grown tremendously, opening the door to improved methods for marrow transplants and to promising therapies for catastrophic diseases—cancer, AIDS, aplastic anemia and autoimmune disorders, among others.

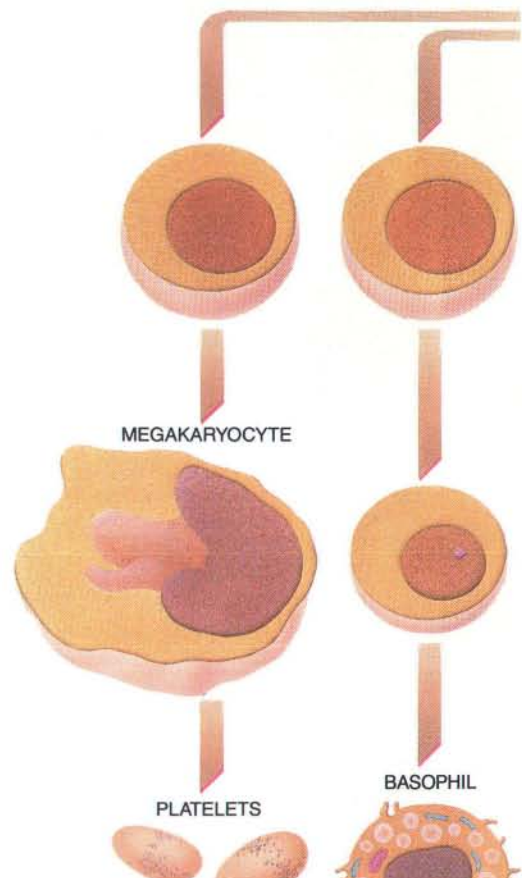
DAVID W. GOLDE has been a pioneer in the study of the development of normal and malignant blood cells; he has also conducted extensive research on the factors that regulate cell growth. Golde earned his M.D. at McGill University in 1966 and completed training in internal medicine, hematology and oncology at the University of California, San Francisco, and at the National Institutes of Health. During the past decade, he has held a number of posts at the University of California, Los Angeles. Recently he moved to New York City to become head of the division of hematologic oncology at the Memorial Sloan-Kettering Cancer Center, where he also holds the Enid A. Haupt Chair in Hematologic Oncology. Golde's hobbies include diving, fishing and horseback riding.

These new therapies will depend on a comprehensive understanding of the nature and function of stem cells. A stem cell may be defined as a cell that can replicate repeatedly and differentiate into various kinds of secondary cells. As the cells differentiate, they commit themselves more and more to a particular lineage until they can form only one kind of cell—a precursor cell that can develop only into an erythrocyte, for example. Any general cell that differentiates into several more specific varieties may be considered a stem cell, but for the purposes of this article, the term "stem cell" refers only to the hematopoietic stem cell.

Hematopoietic stem cells first appear in the human embryo in the yolk sac. They then migrate to the liver as the fetus develops. Blood cells are created in the liver of a fetus, but shortly after birth blood is normally produced solely in the bone marrow. Fetal stem cells differ from adult stem cells in that the former give rise to special types of lymphocytes as well as to red blood cells, which produce fetal hemoglobin. Fetal stem cells seem to have an internal clock that tells them to acquire the characteristics of adult stem cells as an infant matures.

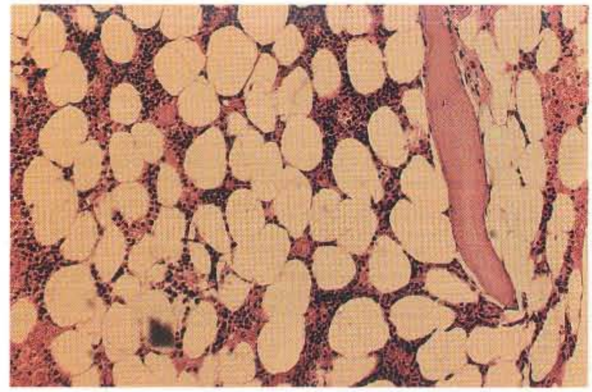
Stem cells have varying degrees of "stemness," that is, the range of more specialized cells that they can create. Some stem cells can replicate extensively but have only a limited capacity for differentiation. The most fundamental cell in this family is the so-called totipotent stem cell; in principle, a single totipotent stem cell can permanently reconstitute the entire blood-producing and immune systems. Stem cells that are less general but that can still differentiate into several lines are called pluripotent.

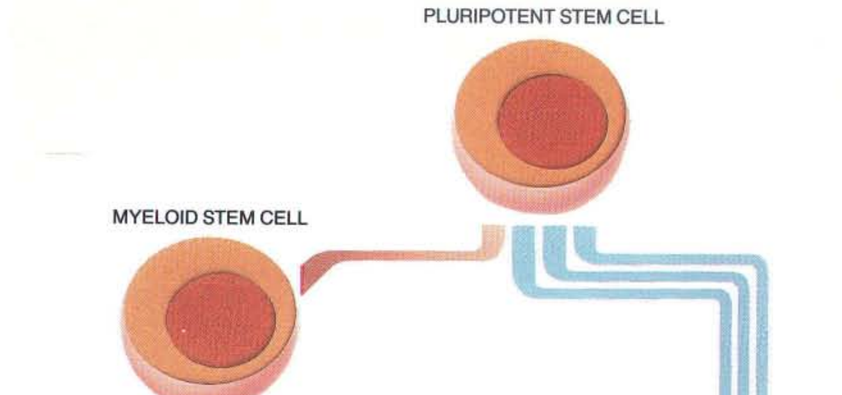
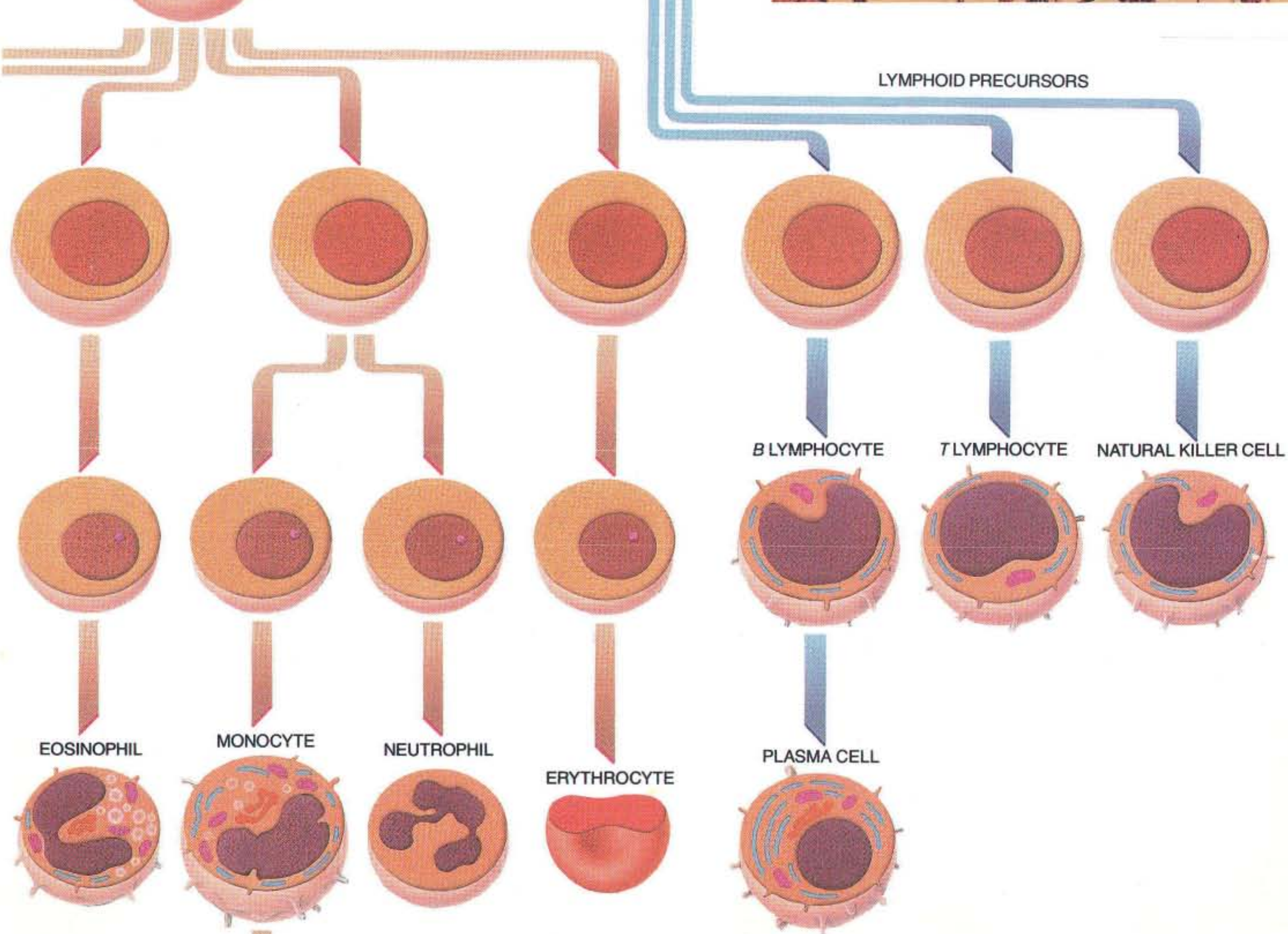
Stem cells are the main ingredient in bone marrow transplants. Bone marrow cells can be kept alive in a cryogenic chamber and then infused into a patient. The stem cells in the transplanted marrow can reestablish the re-

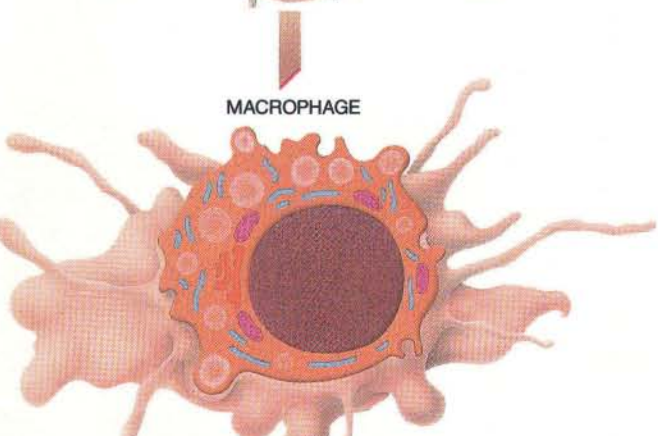


cipient's blood-producing and immune systems. Marrow can be returned to the individual from whom it was taken (autotransplantation), or it can be donated to someone else (allogeneic transplantation).

The precursor cells that derive from stem cells can replicate and differentiate at an astounding rate: an average person creates three to 10 billion platelets, red cells and neutrophils, along with some unknown number of





STEM CELLS DIFFERENTIATE to form the many varieties of blood cells. Some stem cells become lymphoid precursors, which then produce the lymphocytes that constitute the immune system. Other stem cells give rise to the precursors of erythrocytes (red blood cells), platelets (which are essential for clotting) and neutrophils, monocytes, macrophages and other cells that fight infections and clear the body of foreign matter. The bone marrow biopsy (*top right*) shows the reddish liquid in which stem cells reside, along with fatty cells and a splinter of bone.

lymphocytes, every hour. In times of need, the production rate can increase 10-fold or more. The life span of blood cells varies widely. Red cells circulate for about 120 days, during which time a cell may travel more than 300 miles. Platelets stay in the circulatory system for a week or so. Neutrophils remain in the blood for only eight hours before they pass into tissues and then die. Some lymphocytes, in contrast, may survive for years or perhaps even for one's lifetime.

In addition to forming the various cells of the bloodstream, stem cells also appear to be the source of an important class of immune system cells known as macrophages. Macrophages are large cells that resemble monocytes in appearance and function, but unlike monocytes, they are present in most organs in the body, not just the bloodstream. In 1976 E. Donnall Thomas of the University of Washington and I demonstrated that macrophages in the lung derive from stem cells. We examined macrophages in patients who had recently received bone marrow transplants from donors of the opposite sex, making the transplanted cells easy to identify. Within three months after the transplant, all of the lung macrophages we examined were of the donor's sex.

Two years later Robert P. Gale of the University of California at Los Angeles and I showed that liver macrophages also originate from stem cells in the bone marrow. Other researchers have proved that macrophages in the skin and brain, as well as osteoclasts (a kind of macrophage that reabsorbs and remodels bone), originate from bone marrow stem cells.

In 1961 J. E. Till and E. A. McCulloch of the University of Toronto significantly advanced the understanding of where and how stem cells operate. The researchers exposed mice to lethal doses of radiation (thereby destroying the animals' immune and blood-forming systems) and then injected them with bone marrow from a healthy, genetically compatible donor. About 12 days later Till and McCulloch removed the spleens of the irradiated mice and counted the colonies of blood-producing cells growing there. They found that the number of colonies in the mouse spleens reflected the number of stem cells originally injected. These spleen colonies evidently developed from a stem cell population, although they did not necessarily derive from the most primitive, totipotent stem cell.

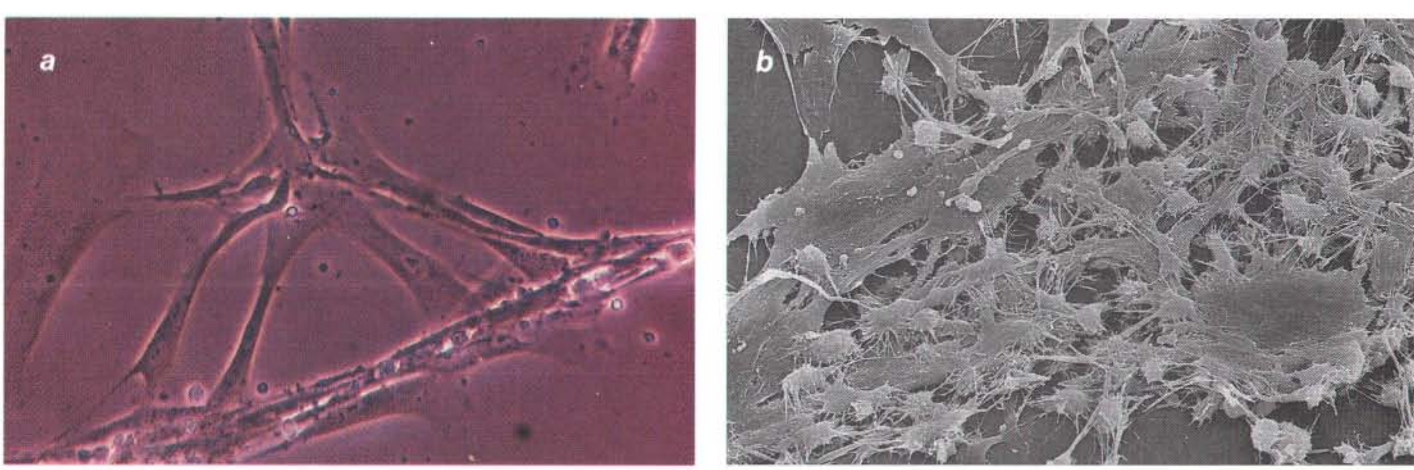
Isolating stem cells from the mass of cells in the bone marrow has proved no easy task. In 1988 Gerald J. Spangrude and Irving L. Weissman of Stanford University, along with several colleagues, sorted through the cells in mouse bone marrow using a series of monoclonal antibodies, complex proteins that bind only to antigens on specific cell types. In this way, they identified a subpopulation of cells, accounting for less than 0.1 percent of the cells in the bone marrow, that could permanently reconstitute the immune blood-producing systems of mice exposed to deadly levels of radiation.

This subpopulation seems to be highly enriched in primitive stem cells. Lethally irradiated mice survived 50 percent of the time if they were injected with only 30 of these cells. Ihor R. Lemischka of Princeton University and his colleagues have conducted analogous experiments designed to separate stem cells from mouse fetal liver. They, too, found a cellular subpopulation, constituting 0.1 to 0.2 percent of the cells in the fetal liver, that contains the totipotent stem cell.

In 1984 Curt Civin of Johns Hopkins University isolated a monoclonal antibody that recognizes a well-known leukemia cell line (KG-1) developed at U.C.L.A. by H. Phillip Koeffler and me. Civin's antibody has proved useful for targeting the human stem cell because it reacts to a cell protein marker, or antigen, called CD34. This marker is found on the most primitive human stem cells and on other blood cell precursors derived from the totipotent stem cell. Cells that bind to Civin's antibody can be separated from the rest of the population. In baboons, CD34-separated bone marrow cells have been shown to reconstitute the hematopoietic system of lethally irradiated recipients. Therefore, pluripotent stem cells must exist among the CD34-positive bone marrow cells, although these primitive stem cells make up only a small part of that population.

Other workers have developed methods for further isolating stem cells from among the cells that bind to CD34. For example, Charles Baum and his co-workers at Systemix, Inc., in Palo Alto, Calif., have made progress in separating out the true human stem cells by means of monoclonal antibodies that positively or negatively select for stemness. Baum's group has pursued a unique approach using immunodeficient white mice, known as SCID mice, that have been implanted with fragments of human thymus and bone. Separated human stem cells injected into the mice replicate rapidly and differentiate, populating the thymus fragments with human lymphocytes and the bits of bone with primitive myeloid cells. In this way, it is possible to study human stem cells in a living specimen.

For therapeutic purposes, one would



ARTIFICIAL BONE MARROW SURFACES, or stromal layers, permit the study of the behavior of stem cells and derived blood cells in a long-term culture. Bone marrow cultures (*a*) contain many of the cells, hormones and other proteins nor-

like to be able to control stem cell differentiation and to cause pluripotent stem cells to replicate. How a stem cell "decides" whether to replicate or to differentiate remains a central unanswered question of stem cell physiology. Two broad schools of thought exist regarding stem cell differentiation. The deterministic view holds that external influences, including hormonal signals, direct stem cell differentiation. The competing, stochastic view contends that the decision to self-renew or to differentiate, as well as which lineage to follow, occurs randomly.

To help settle this debate, Makio Ogawa of the Medical University of South Carolina in Charleston has devised a method for growing human stem cell colonies in a semisolid gel. He removed single cells from the early-forming colonies and used them to start secondary colonies. Ogawa found that the cells in these secondary colonies developed into a variety of cell types, indicating that the stem cells in the original colonies randomly differentiated along several lines. When he separated newly divided pairs of stem cells to establish two independent colonies, Ogawa discovered that these, too, exhibited random differentiation. Such results are consistent with a stochastic model of stem cell behavior.

The deterministic concept implies that the surrounding chemical environment directs the differentiation of stem cells or somehow commits them to one of several possible pathways of development. Supporting (stromal) cells and various molecules that bind to the stem cells in the marrow could provide signals for stem cell differentiation in ways that cannot be measured when cell colonies are studied in cultures that lack the supporting tissues.

At some point, a stem cell expresses the receptors that make it sensitive to the hormones in the body that regulate the production of blood cells. The stem cell is then able to proliferate in response to the hormonal signal. This stage is critical in the differentiation process. Nobody knows, however, what regulates the initial expression of these receptors or precisely which receptors exist on the most primitive, totipotent stem cells. I conclude that the stochastic and deterministic theories of stem cell development are not mutually exclusive and, in fact, that both mechanisms probably occur.

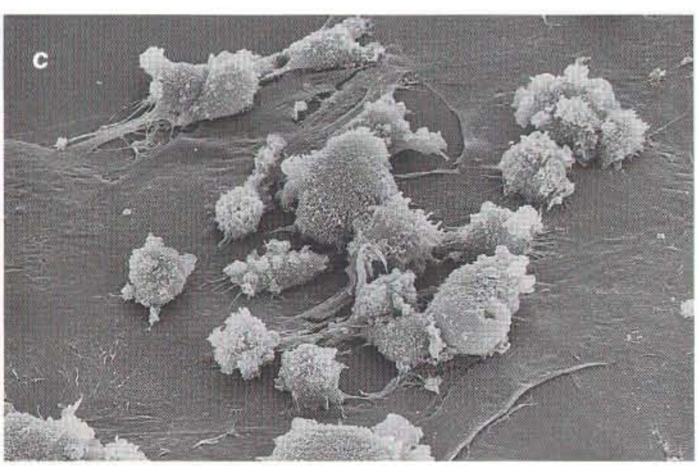
Researchers trying to learn more about stem cell behavior would like to study the cells inside the bone marrow, but such a procedure is highly impractical. In the 1970s Michael Dexter and his colleagues at the Paterson Institute for Cancer Research in Manchester, England, created a culture system that can sustain human stem cells in the laboratory, thereby making it possible to observe their growth and development under conditions similar to those prevailing in human bone marrow. In real marrow, stromal tissues provide a setting conducive to the development of blood cells. In Dexter's system, blood-producing cells (including stem cells) grow in a flask lined with an "artificial" bone marrow stromal layer. This layer is composed of cells and organic material extracted from the bone marrow.

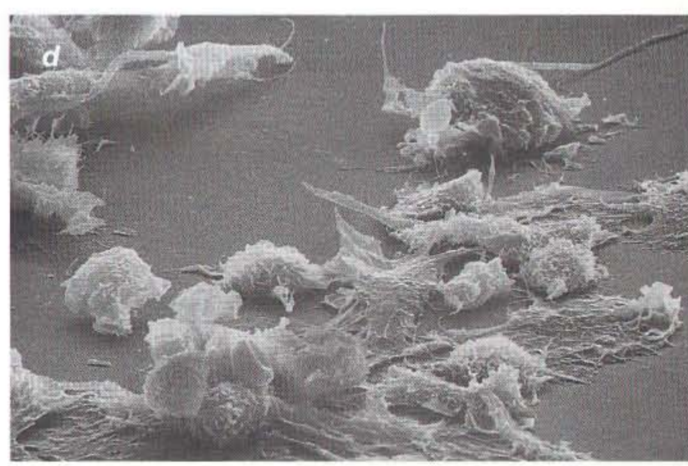
Many components of natural marrow are present in this cultured layer, including fibroblasts, fat cells, endothelial cells and macrophages. The culture also contains many of the matrix proteins (such as collagen, fibronectin, laminin and hemonectins) that appear to play a role in hematopoietic cell replication and differentiation. The cells lining the flask are capable of producing hormones that regulate cell division and other aspects of blood cell production and differentiation.

Other constituents in the adherent layer may facilitate the action of hormones that promote the growth of blood cells. Long-term cultures permit blood cell production to continue for as long as two to three months, enough time for researchers to analyze the influences that regulate the growth and development of stem cells and to identify the poorly understood roles of various stromal elements. These cultures may someday be used to grow large numbers of stem cells for use in transplant therapy.

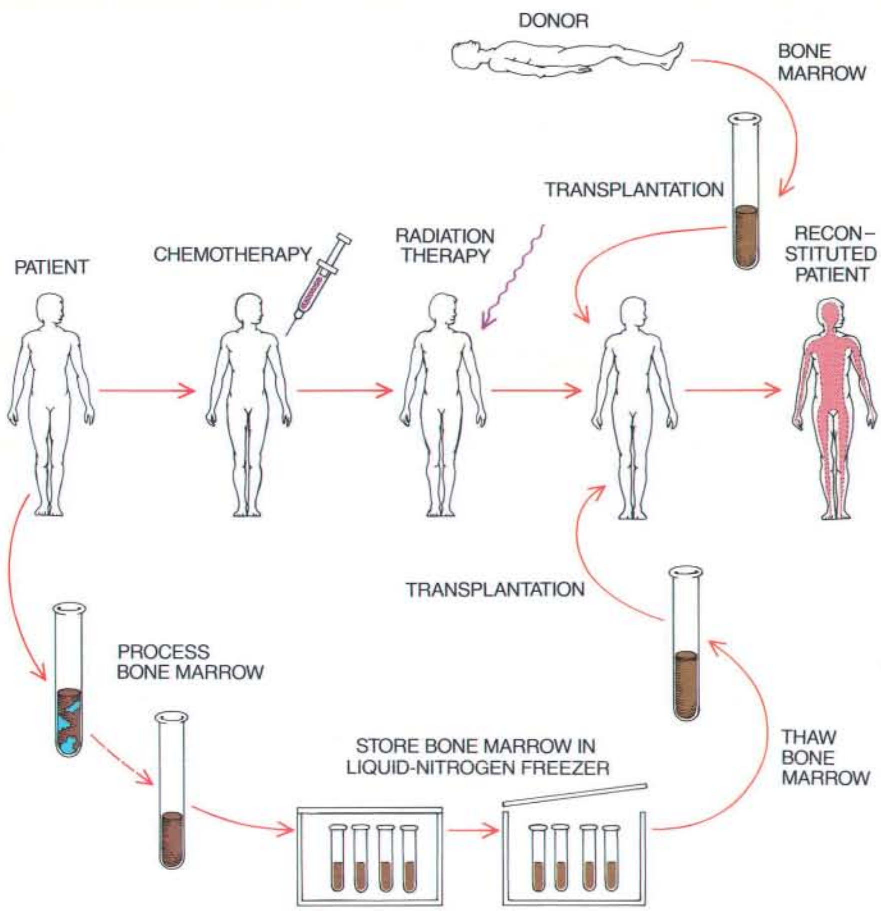
Building on these studies, several recent experiments have revealed new details about how hormonal factors regulate hematopoiesis and how the marrow environment affects stem cell activity. These factors may be extremely important for treating diseases because they may hold the key to coercing primitive stem cells to replicate. Several hormones have been found to stimulate the replication of early-type cells, precursors of the other blood cells but somewhat differentiated and hence not true totipotent stem cells. These hormones include granulocyte colony-stimulating factor (G-CSF), interleukin-6, interleukin-11 and a recently described molecule often known as stem cell factor.

Stem cell factor is of particular interest because it has been identified as the hormone that interacts with a cell receptor produced by the cellular oncogene *c-kit*. The oncogene receptor exists on pigment cells (melanocytes) and blood-producing cells. A strain of mice that has been bred to have anemia and pigmentary abnormalities (meaning it produces malfunctioning red blood





mally present in marrow. Over several weeks blood cells begin to develop on the cultured stromal layer (*b* and *c*). Eventually the blood cells adhere to and interact with the artificial layer (*d*), much as they do in bone marrow in the body.



BONE MARROW TRANSPLANTATION is used to treat patients whose stem cells have been injured by leukemia, cancer or unknown toxins. Marrow donors and recipients must have compatible tissue types; otherwise the transplanted stem cells will not engraft. A patient's marrow can be stored away before he or she undergoes chemotherapy or radiation therapy for cancer. Afterward the marrow is injected into the patient to replace the stem cells destroyed by the therapy.

cells and melanocytes) is also known to have defective *c-kit* oncogene receptors. Researchers recently demonstrated that another type of genetically anemic mouse whose bone marrow is defective lacks the ability to produce stem cell factor. Evidently, stem cell factor acts on true stem cells, although evidence suggests it is not the long-sought self-renewing factor. These findings are clarifying the connection between the hormone mixtures in the bone marrow and the behavior of the stem cells.

The ultimate goal of the research on stem cells is to improve treatments for blood and immune system diseases. Bone marrow transplants are performed in patients whose immune and blood-forming systems have been devastated by leukemia, cancer, chemotherapy, radiation therapy or unknown causes. At present, the only way of acquiring enough stem cells is to extract marrow from a donor's bones with a needle and syringe, an involved process that usually requires general anesthesia.

Bone marrow transplants also present numerous medical hurdles. The recipient must receive a steady supply of fresh red cells, platelets and antibiotics for several weeks until the transplanted stem cells begin producing large quantities of mature blood elements. The recipient's immune system must be sufficiently suppressed so that it will not reject the transplanted stem cells. At the same time, the immune system cells produced by the donor stem cells may recognize their new host as foreign—a reaction known as graft versus host disease (GVHD)—in which case they may cause lethal tissue and organ damage. The recipient must therefore be protected from attack by the newly developing immune system.

For patients who have acute leukemia or other cancerous blood diseases, the malignant cells must be eradicated for the transplant to be successful. In these cases, a mild form of GVHD, called graft versus leukemia, is actually desirable. Immune cells derived from donor stem cells appear able to destroy or to contain the relatively few remaining leukemia cells. Molecular evidence shows that some patients apparently cured of myelogenous (marrow-based) leukemia by an allogeneic marrow transplant still harbor a small population of leukemia cells. The evident ability of transplanted stem cells to contain the leukemia cells in the recipient is valuable for therapy but difficult to control because the graft versus leukemia effect is so closely related to GVHD.

Because transplanted stem cells can reconstitute the immune system, the technique has been used to treat genetic diseases in which lymphocytes malfunction, such as severe combined immunodeficiency syndrome. Stem cell transplants can also treat metabolic diseases involving disorders of the macrophages, such as osteopetrosis (which leads to overly dense bone) and severe Gaucher's disease (characterized by anemia and distortions of the bones). Likewise, stem cell transplants can cure congenital disorders of the blood production process—such as thalassemia and sickle cell disease (defects of the oxygen-carrying hemoglobin in the red blood cells), Fanconi's anemia (a stem cell defect that leads to bone marrow failure) and chronic granulomatous disease (a severe enzyme defect in white blood cells).

Bone marrow donors are usually siblings whose tissue types are compatible and sometimes unrelated donors who are matched to the recipient by a method called HLA typing. HLA tissue typing has several advantages: stem cells can be made available to persons who do not have matched siblings; multiple donors may be available for a given recipient; and the graft versus leukemia effect can take place. Many registries of HLA-typed donor candidates exist in Europe and in the U.S. The U.S. National Marrow Donor Program, which is run under the aegis of the National Institutes of Health, now has approximately 330,000 typed donors on file.

Despite such registries, the chance of finding a compatible, unrelated marrow donor remains low, about one in four for whites; the likelihood of a match is much lower for minorities and those of mixed ethnic heritage because minorities are poorly represented in the registries. Furthermore, marrow from an unrelated donor fails to engraft or is rejected in 10 to 20 percent of all cases, and serious GVHD occurs approximately 50 percent of the time.

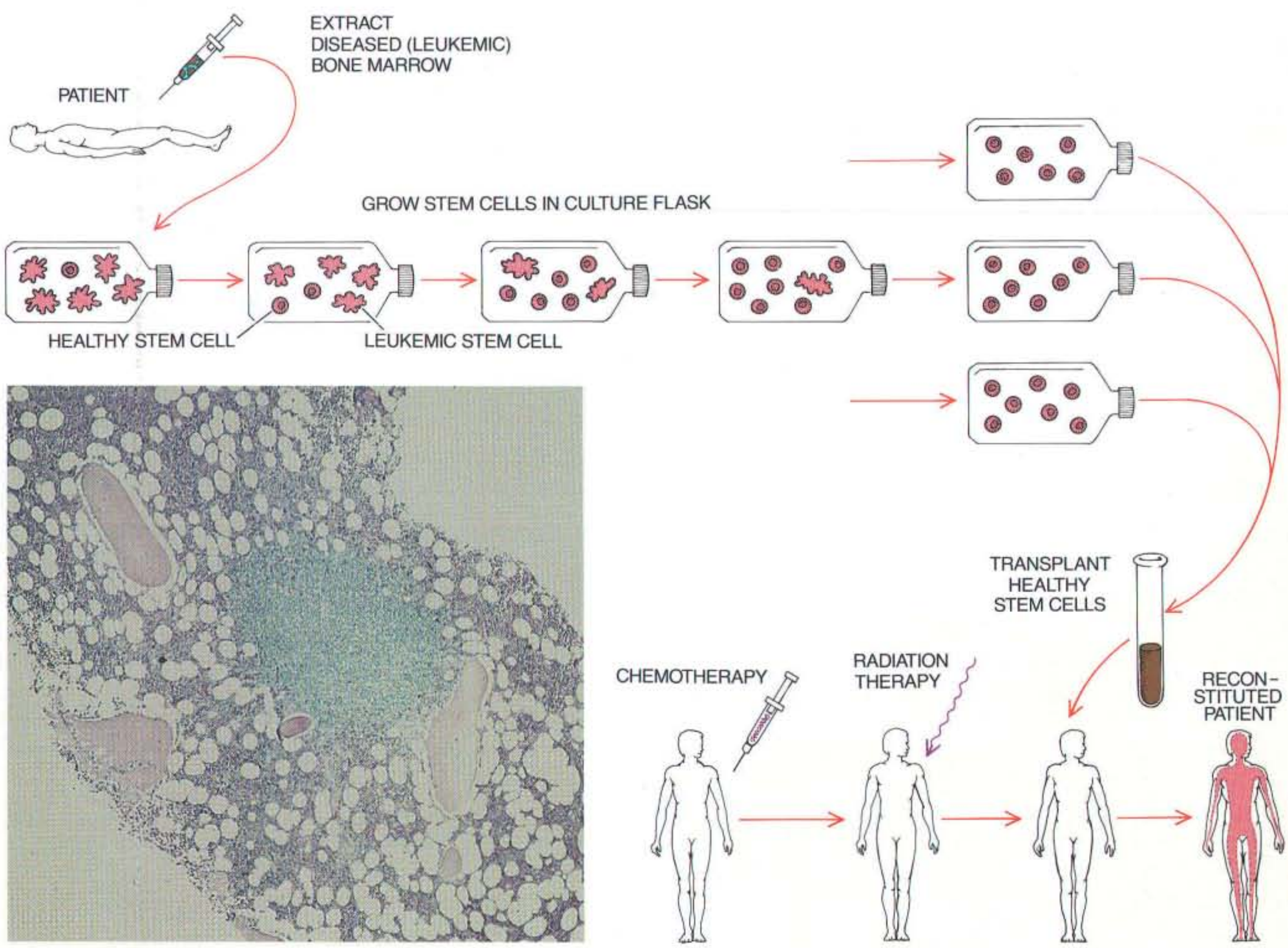
Marrow need not be donated by someone else. In a procedure known as autologous transplantation, a patient's own stem cells are collected and stored outside the body while chemotherapy or radiation therapy is administered in an attempt to obliterate the malignant cells. Autologous transplantation permits the use of high-dose chemotherapy and irradiation without the risk of permanently destroying a patient's blood cell-forming capacity and immune system. The bone marrow is extracted, frozen and stored; it is later returned directly into a vein. (The stem cells eventually home to the bone marrow.) In this way, autologous marrow transplants circumvent the potentially fatal effects of cancer chemotherapy on the blood-producing cells.

Autologous transplantation eliminates the need to find a compatible marrow donor and bypasses the risk of GVHD. On the other hand, the restored stem cells do not normally produce a graft versus tumor effect. Also, patients who could most benefit from an autologous transplant may have bone marrow that has already been invaded by cancer cells, especially in patients having leukemia or lymphoma (cancerous growth in the lymph system).

The ability to separate malignant stem cells from the healthy ones in a patient's bone marrow could have important medical implications, and so researchers have tried several ways to purge bone marrow of malignant cells. Their methods include using monoclonal antibodies that incorporate complement (destructive enzymes that bind to antibodies) or that have attached toxins. Another approach involves using chemotherapy to treat the extracted marrow while it is outside the body in an attempt to destroy the malignant stem cells.

None of the purging techniques yet attempted have proved clearly effective, and they may in fact delay engraftment of the transplanted cells. Some workers have proposed cleansing bone marrow of certain tumor cells by selecting out CD34-positive cells. Other monoclonal antibodies may also be capable of separating normal stem cells from leukemic ones.

Connie J. Eaves and her colleagues at the University of British Columbia, along with Dexter and his co-workers, have found an intriguing means of approaching such separation. They discovered that the long-term culture system tends to inhibit the growth of leukemic cells in the marrow as compared with normal growth of stem cells. The two groups examined the ratio of leukemic to normal cells in cultures grown from bone marrow from leukemia patients. The researchers observed that whereas leukemic cells have a growth advantage over normal stem cells in the body, they had a distinct disadvantage in the long-term cultures. Others have reported similar findings for different leukemic cells; the possibility of preferentially growing healthy stem cells may hold for other malignancies



BONE MARROW CULTURES seem to encourage healthy stem cells to reproduce more rapidly than leukemic ones. Over time one might be able to derive a population of healthy stem cells from diseased marrow (such as the lymphoma-afflicted marrow shown in the inset image). If so, patients could undergo chemotherapy or radiation therapy to kill off their diseased cells and then receive an injection of healthy stem cells derived from their own bodies.

as well. Eaves, Dexter and their colleagues have attempted to use the long-term culture system as a means of purging leukemic cells from a patient's bone marrow while maintaining a supply of normal, healthy stem cells. Their procedure and general strategy appear promising.

Regardless of their source, the stem cells must be transplanted in huge quantities so that a patient's immune and hematopoietic systems quickly reestablish themselves. The number of stem cells required for a successful engraftment is quite uncertain, however. Because nobody knows how many stem cells are present in a given bone marrow sample, my colleagues and I have had to rely on experience and extrapolations from animal data to estimate cell dose in human transplantation. In general, we have found it necessary to transplant 200 million bone marrow cells per kilogram of body weight. Lower doses tend to increase the risk that the transplanted cells will fail to graft or will be rejected. The need for a large number of bone marrow cells requires multiple extractions. About 500 to 1,000 milliliters of bone marrow is removed from the donor, processed through filters, and then delivered to the recipient or put in frozen storage for subsequent transplantation back into the donor.

Bone marrow transplants would be much more effective if a way could be found to accelerate the process of engraftment. Recent results from many medical research centers have shown that administering the hormones GM-CSF and G-CSF, which stimulate blood production, markedly reduces the time necessary for stem cells to engraft and for the peripheral white blood cell count to return to safe levels.

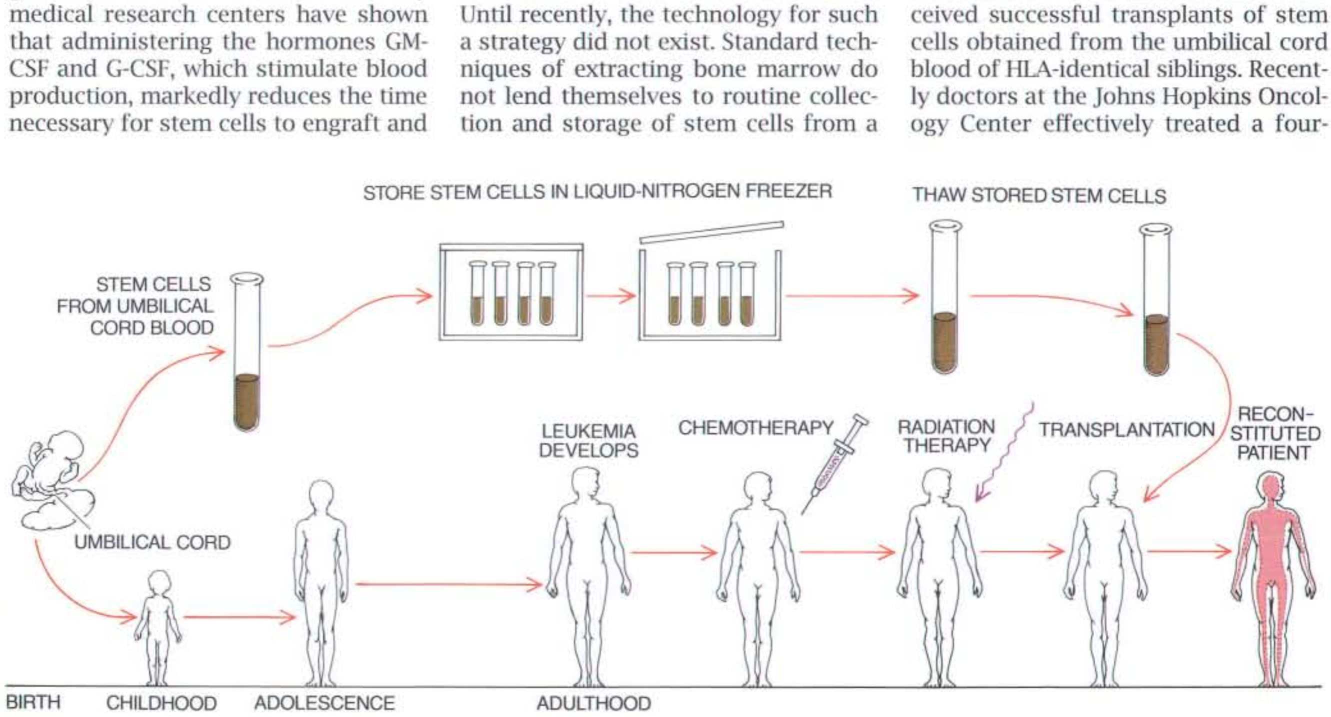
Such hormones may prove useful in other ways as well. Some investigators have found that adding stem cells from the peripheral blood to those from the bone marrow significantly increases the rate of engraftment. Extracting sufficient numbers of stem cells from peripheral blood is a complicated procedure that involves repeatedly passing the blood through a cell separator. Administering GM-CSF or G-CSF drastically increases the number of stem cells in the blood, improving the feasibility of transplanting stem cells from peripheral blood.

When researchers produce effective techniques for isolating a fairly pure sample of pluripotent stem cells and for accelerating the grafting process, creative strategies for storing and transplanting bone marrow will become possible. For example, if a single marrow extraction performed under local anesthesia (containing 10 to 15 milliliters of marrow) could provide enough cells for engraftment, individuals could easily store their own cells for possible later use. The marrow donation process also would be considerably simpler and less burdensome.

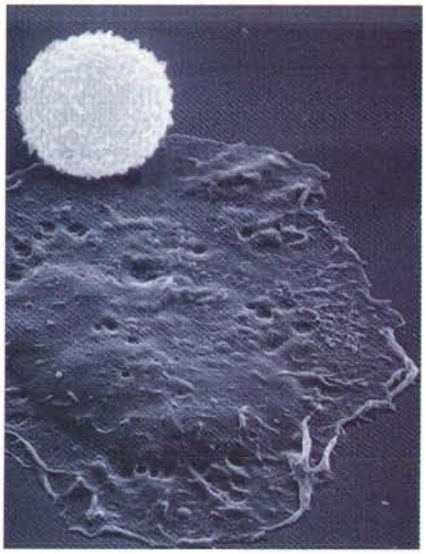
A particularly forward-looking strategy would be for healthy people to have their stem cells placed in permanent storage for a time when the cells might be needed to treat a serious disease. Until recently, the technology for such a strategy did not exist. Standard techniques of extracting bone marrow do not lend themselves to routine collection and storage of stem cells from a broad segment of the population. The process of obtaining enough stem cells for effective transplants could be made much simpler if a system existed for growing stem cells in vitro, that is, outside the body.

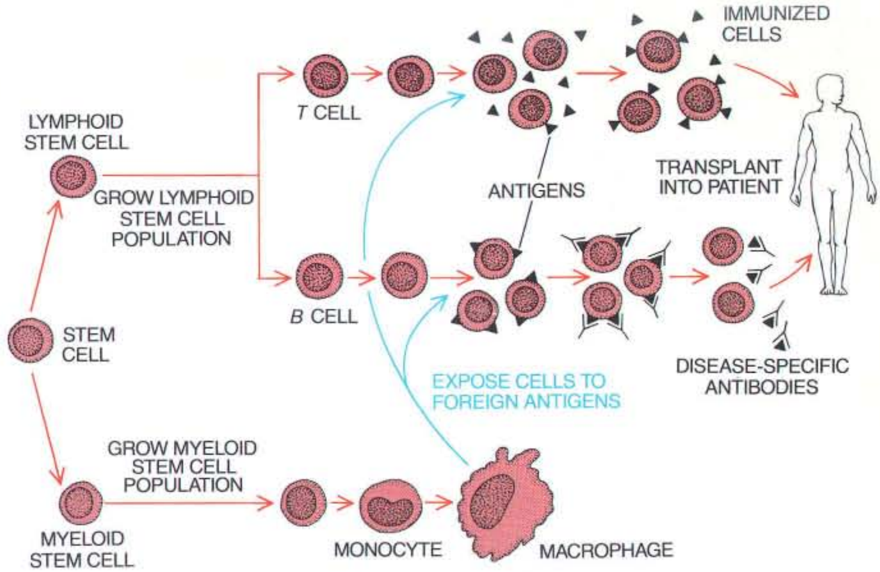
The long-term cultures previously described already suffice to keep stem cells alive; modifying that technology could allow a small seed culture to develop into a sizable cell population. Administering hematopoietic hormones such as GM-CSF and G-CSF may then help expand the stem cell population in the body after transplantation. The ability to enhance engraftment using such hormones, along with the prospect of being able to cause stem cells to replicate rapidly both inside and outside the body, suggests that physicians may soon be able to perform successful transplantation starting with a small initial sample of stem cells.

Umbilical cord blood may prove an important source of such an initial sample. Workers have known for nearly two decades that cord blood contains blood cell progenitors. Using his stem cell colonies, Ogawa showed in 1987 that umbilical cord blood contains pluripotent stem cells. Edward A. Boyse, formerly at Memorial Sloan-Kettering Cancer Center, along with Harold E. Broxmeyer of Indiana University and Elaine Gluckman of Saint-Louis Hospital in Paris, conceived of using cord blood for transplantation. They have reported that two patients who were afflicted with Fanconi's anemia received successful transplants of stem cells obtained from the umbilical cord blood of HLA-identical siblings. Recently doctors at the Johns Hopkins Oncology Center effectively treated a four-



UMBILICAL CORD BLOOD contains active stem cells. Because cord blood cells can be stored for long periods, every person could have a supply of healthy, compatible stem cells available whenever a medical crisis might arise.





CUSTOMIZED BLOOD CELLS may soon permit radical new therapies. Lymphocytes (*top left*) and macrophages (*bottom left*) might be grown from cultured stem cells. *T* lymphocytes could be exposed to antigens and then released into the body, where they would kill cancerous or virus-infected cells. In a similar way, *B* lymphocytes could be trained to make antibodies directed against specific diseases or disorders. Macrophages help to present antigens to the *T* and *B* cells.

year-old leukemia victim using transplanted umbilical cord blood cells.

At present, cord blood is normally discarded after birth; it could become a valuable source of stem cells that could, theoretically, be kept available thoughout an individual's lifetime. Stem cells and lymphocytes from cord blood would lack all the disease resistance acquired through life, and so they would lead to reconstitution of a "naive" or inexperienced immune system that would need time to acquire the appropriate disease immunities.

The ability to store stem cells from many or all individuals—especially the capacity for routine storage of hematopoietic stem cells collected at birth—would have profound medical implications. A supply of stored stem cells would be instantly available for the kinds of situations that currently call for autologous transplantation. Furthermore, the problems associated with purging tumor cells from diseased blood or bone marrow would be obviated. Stored samples of stem cells might also be available for allogeneic transplantation, although that procedure raises many logistic and ethical concerns.

The prospect of storing one's own stem cells ready for use at any moment opens up possibilities for disease treatments that go well beyond reconstitution of the blood-producing system. As researchers learn to grow certain stem cell lines in the laboratory, they should also be able to discover ways to remove a patient's stem cells, manipulate them for some therapeutic effect and then reintroduce them. For example, one might be able to alter stem cells so that when transplanted back, they differentiate into immune cells able to carry out specific new functions. Immune cells might also be altered at more advanced stages of development. For example, *B* lymphocytes, which specialize in producing antibodies, could be grown and immunized in the laboratory to cause them to produce antibodies against specific diseases.

All kinds of intriguing possibilities arise. Could one "teach" *B* cells in vitro to make antibodies against cancerous cells or against infectious agents such as HIV (the AIDS virus)? Might it be feasible to grow in the laboratory cytotoxic *T* lymphocytes ("killer" white blood cells) that have been specifically sensitized to recognize and kill tumor cells or virus-infected cells?

These strategies are not as fanciful as they may seem. David Baltimore of the Rockefeller University has suggested that autologous *T* cells could be rendered resistant to infection by HIV, a notion he has dubbed "intracellular immunization." Eli Gilboa of Sloan-Kettering has isolated a gene from HIV, known as *tar*, that binds and blocks a protein the virus needs in order to replicate. Gilboa has managed to introduce this gene into cultured lymphocytes. The cultured cells that express *tar* are resistant to HIV infection. It remains to be seen whether techniques that work in the test tube will work as well in humans.

Continuing research will enable medicine to take new approaches to treating human diseases, ones that will embrace multiple means of marshaling and enhancing the body's natural defenses. The road to improved disease prevention and cure may eventually involve specific and general arming of the cells of the immune system to deal more effectively with the hostile biological environment all around. The central role of the stem cell in the growth and maintenance of the human blood-producing and immune systems ensures that it will be crucial for achieving these goals.

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The Origin of Horseback Riding

Analysis of horse teeth from the Ukraine proves that riding began 6,000 years ago, much earlier than had been supposed. The innovation affected the dispersion of culture and language

by David Anthony, Dimitri Y. Telegin and Dorcas Brown

On the day when a human first jumped onto the back of a horse and surveyed the world from that elevated post, the course of history was changed. A French hippophile once observed, with only a little hyperbole, that man, threatened by elements that conspire to destroy him and by beasts stronger and faster than he, would have been a slave if the horse had not made him a king.

Horseback riding has generally been supposed to have begun in central Asia a mere five centuries or so before the appearance of cavalry in armies of the Middle East around 1000 B.C. This view is mistaken. New evidence based on dental wear caused by a bit in a prehistoric horse indicates that riding began much earlier. The epochal relation between horse and rider originated in a Copper Age society known as the Sredni Stog culture, which flourished in the Ukraine 6,000 years ago. Riding therefore predates the wheel, making it the first significant innovation in human land transport. Moreover, the time and place of the earliest riders lend new support to the old theory that horsemen from the steppes of Eurasia helped to spread the Indo-European family of languages, now the most widely dispersed in the world.

Before about 4300 B.C., horses were exclusively wild and ranged naturally through the vast belt of grasslands that extended from the Ukraine east to the Tien Shan and Mongolia. Small horse populations lived in central and western Europe, but the animals were important in the human diet only at the edges of the steppe grasslands, where they must have formed large herds. Like the buffalo in North America, they were the primary large grazing animal of the steppes.

Horses recovered from prehistoric sites might have been used in three ways: as wild game, as domesticated sources of meat and as mounts. Ways to distinguish these uses have been suggested from studies of two populations of modern feral horses. Joel Berger of the University of Nevada has studied the mustangs of the Granite Range of Nevada, and Ronald R. Keiper of Pennsylvania State University and Daniel I. Rubenstein of Princeton University have studied the ponies of the Eastern Shore barrier islands of Virginia and Maryland. The ethologists found that horses in the wild naturally form two primary social units: bachelor bands and harems led by a single stallion.

Bachelors roam widely and unpredictably, whereas stallion and harem bands follow habitual routes, producing dung-lined trails that would have made these bands easy for hunters to track. The remains of hunted horses should therefore consist primarily of adult mares and their immature offspring. In contrast, the horses chosen for slaughter from a domestic herd should include a higher proportion of young males, who are unruly and not needed for the increase of the herd.

The sex and age structures revealed in the bones of the horses eaten by Copper Age humans should therefore indicate whether the horses were wild or domesticated. Unfortunately, determination of the sex of horse skeletons is often impossible, because it depends on the preservation of the upper or lower jaw tooth row, which in males contains canine teeth that are normally absent in females. But because there is little meat on a horse's jaw, relatively few were brought to the kitchens, whose leavings constitute the principal archaeological trove. Attempts to identify the earliest domesticated horses have consequently depended on traits other than sex, primarily cranial measurements and lower leg bone dimensions, neither of which yet provides conclusive evidence for domestication.

The most important archaeological site for the study of early horse keeping is Dereivka, a hamlet excavated by one of us (Telegin) between 1960 and 1967 and again in 1983. The site, one of hundreds identified with the Sredni Stog culture of the Ukrainian Copper Age, is 155 miles (250 kilometers) south of Kiev on the west bank of the Dnieper River, in an ecological zone that forms a transition between the forest steppe to the north and the true steppe to the south. The Sredni Stog culture, named after an island in the Dnieper where the first site of this type was excavated, dates between 4300 and 3500 B.C. Four radiocarbon dates from Dereivka indicate that it was occupied around 4000, give or take a few centuries.

The recovery of grindstones and flint sickles indicates that the Sredni Stog people practiced agriculture. The plenitude of bones of cattle, sheep, goats and pigs suggests that they also bred stock. Horses, however, are what make the culture distinctive economically.

As a percentage of food refuse, horse bones are about twice as important for the Sredni Stog people as they had been for earlier cultures in the region. Not only did they eat more horsemeat, they ate it at sites farther north, in well-watered, forested catchments where feral horses rarely roam. The people must have brought the horses there.

The increased use of horsemeat sug-

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gests that the culture domesticated the animal around this time as a source of food. It would have been a particularly convenient source: horses, unlike cattle and sheep, are native to the region and hence require less care—particularly during the lean winter months. Not long after horses were first corralled, someone must have hit on the idea of riding one.

Dereivka has yielded evidence documenting these trends toward increased exploitation of horses. The 2,412 horse bones in its refuse piles (probably accumulated in the course of several reoccupations of the site) constitute 61.2 percent of all the identifiable animal bones. They represent at least 52 animals—probably many more—for a total of 15,000 pounds of meat. That amount would account for 60 percent of the meat weight of the fauna found at the site.

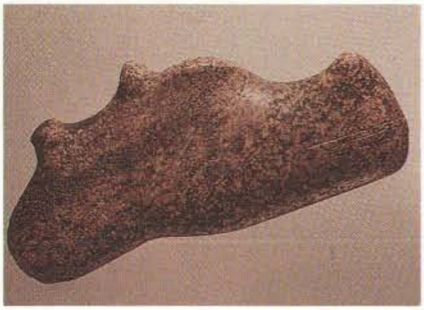
Only six mandibular fragments can reliably be assigned a sex, but all are male. That finding suggests that most of the animals at Dereivka—in fact, a striking preponderance—were male. We know that a wild harem band would yield only about 30 percent males, counting immature offspring, and that a random harvest of a wild horse population would yield somewhat less than 50 percent males. It appears, therefore, that the horses were culled from a managed domestic herd. On the other hand, recent analysis of the ages of the Dereivka horses indicates that most of them were killed between six and eight years of age, older than one would expect for a cull of young bachelors. The site probably contains the remains of both wild and domesticated horses.

The most spectacular find was a horse that had been treated very differently from the others. It was a stallion, seven or eight years old, whose head and left foreleg were found in a ritual deposit with the articulated remains of two dogs. The three animals appear to have been brought together intentionally, in the form of hides or pelts with the entire head and the bones of the foreleg or of the spine still attached. Nearby, workers found a clay figurine shaped like a boar and fragments of others that resembled humans. There were also two perforated pieces of antler that appeared to be the cheekpieces of a bit.

The entire assemblage is a cult deposit: the grouping of horse, dogs and anthropomorphic figurines clearly indicates the horse's domesticated status. The ritual custom in which a horsehide with the head and feet attached is displayed on a pole to mark a sacred location is widely documented in pre-Christian Europe. The rite was conducted well into this century among the Buryat and Oirot peoples, who live between the Altai Mountains and Lake Baikal in Soviet Asia; it may persist there to this day.

The Dereivka cult stallion clearly dates to the Sredni Stog culture. It was found on the ground surface that existed in the Copper Age, where it either fell or was placed, eventually to be covered by Sredni Stog refuse. These details of discovery are consistent with what would be expected for a pole-mounted offering of a head and hide and make it very unlikely that the cult stallion came from an intrusive pit dug by people who came later.

HORSEHIDES hang from poles in a Danish re-creation of a rite of pre-Christian Europe. A comparable stallion, found beside two dogs in a 6,000-year-old Ukrainian site, bears dental bit marks. It is the oldest known mount in the world. The assemblage recalls Indo-European myths of a horse that bears souls to the gates of Hades, where dogs stand guard.



HORSE DOMESTICATION is poorly attested in Copper Age artifacts, such as this horse-head "scepter" (*left, top*) from Drama, in Bulgaria. The first clear evidence dates to this Bronze Age rock carving of horse and rider (*left, bottom*) at Kammenaya Mogila, the Ukraine. Horsemen quickly spread eastward (*map*) into unoccupied steppes but took longer to penetrate settled areas to the west. Horse-drawn chariots reached the Middle East by 1800 B.C., some 2,000 years after riding began.

The antler cheekpieces—if that is what they are—are similar to others that have been cited as circumstantial evidence for Copper Age riding. These include a pair from a Sredni Stog grave at Aleksandriia (which lacked horse remains); some have also been recovered from coeval sites in Poland and eastern Germany. But although similar antler cheekpieces were certainly used 2,000 years later as a part of Bronze Age horse harnesses, these Copper Age examples do not provide absolute proof for the existence of riding.

Another suggestive group of artifacts, analyzed in detail by one of us (Telegin), is the polished stone mace heads that have been recovered from a wide range of late Copper Age sites in the steppes and adjacent parts of southeastern Europe. The earliest ones do not appear to have been shaped to portray animals, but the later specimens, from 3500 to 3000 B.C., are carved to represent horses' heads, occasionally with suggestions of harness straps. These later objects seem to be associated with a post-Sredni Stog culture known as the Yamna. They combine the image of a horse with the symbolism of wealth, being made, for the most part, of the exotic stone porphyry. The mace itself also symbolizes military power. No other animal is represented similarly in Copper Age Europe. Yet even so, the maces do not prove horseback riding.

Because there were no artifacts that clearly proved when riding began, we decided to look in the horse's mouth. We assumed that if the earliest ridden horses were bitted, even with rope bits, their premolar teeth would bear microscopic marks. This initial assumption was greeted with doubt by several veterinarians, who pointed out that the bit ideally remains on the soft tissues of a horse's mouth, where a slight tug on the reins can cause intense discomfort, providing control over the animal. A properly adjusted bit should rest on the horse's tongue and gums in the space between the incisors and the premolars [*see top illustrations on opposite page*].

But as horse trainers have told us, bits do not always rest where they should. This practical wisdom was confirmed by X-ray fluoroscopic photographs of horses champing on their bits, taken by Hilary M. Clayton of the University of Saskatchewan. The photographs showed that if the bit is not perfectly adjusted, the horse can elevate and retract its tongue, raising the bit back onto its forward premolars. The fleshy corners of the mouth are positioned far enough forward of the premolars so that the horse must pull the bit into its cheeks and grasp it firmly between its premolars in order to prevent the cheeks from pushing it forward onto the gums.

A horse that habitually fights the bit will therefore move it repeatedly onto the anterior part of the occlusal (chewing) surface of its forward premolars, where its precarious grip causes the bit to slip over the prow of the tooth. The enormous strength of the horse as it squeezes the bit between its teeth and the tendency of the bit to slip back and forth over the prow of the tooth cause bit wear.

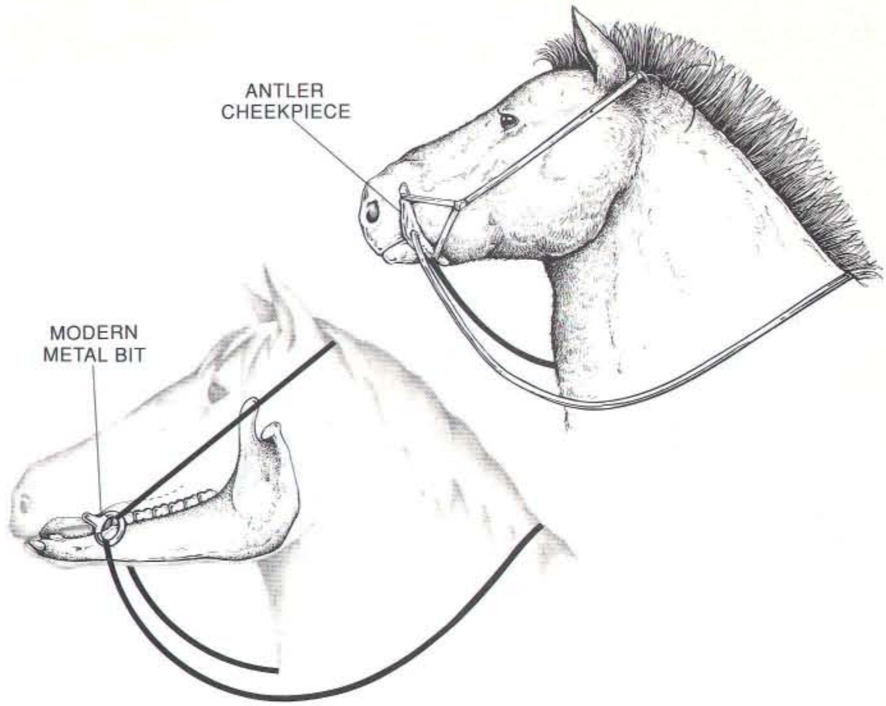
Two of us (Anthony and Brown) examined the lower premolar teeth of 10 modern domestic horses that had been bitted and of 20 feral horses from Nevada and the barrier islands of Virginia—animals that had never been bitted. Under a scanning electron microscope, the damage caused by a bit was clearly distinguishable from that caused by natural occlusal wear. A bit causes damage that is distinctive in four ways. First, the location of the damage is consistent: the occlusal enamel of the first cusp is scarred on the cheek side of the tooth, on the tongue side and on the prow. Second, the scars form a characteristic pattern. Spalls (small fractures) radiate from the center of the raised enamel surface, sometimes joining to form trenchlike breaks that run along the length of the enamel ridge. Third, the bit's movement back and forth over the broken enamel produces irregular areas (called abraded step fractures) within spalls. Finally, the first cusp is often beveled, or worn down, toward the front of the mouth.

On average, 3.56 millimeters of the tooth prow are worn away in modern horses that show the microscopic traits of bit wear. But wear averaging only 0.82 millimeter is found in the premolars of feral horses. Moreover, the occlusal enamel of these horses is generally quite smooth, completely lacking the heavy scars that covered the first cusp of bit-worn horses. About a third of the feral horses do exhibit some fracturing of the enamel on the cheek side of the first cusp, but never on the tongue side. (The damage to the cheek side results naturally from the way horses chew.) Even in these cases, no feral horse has ever been found to bear dental patterns that could be mistaken for bit wear.

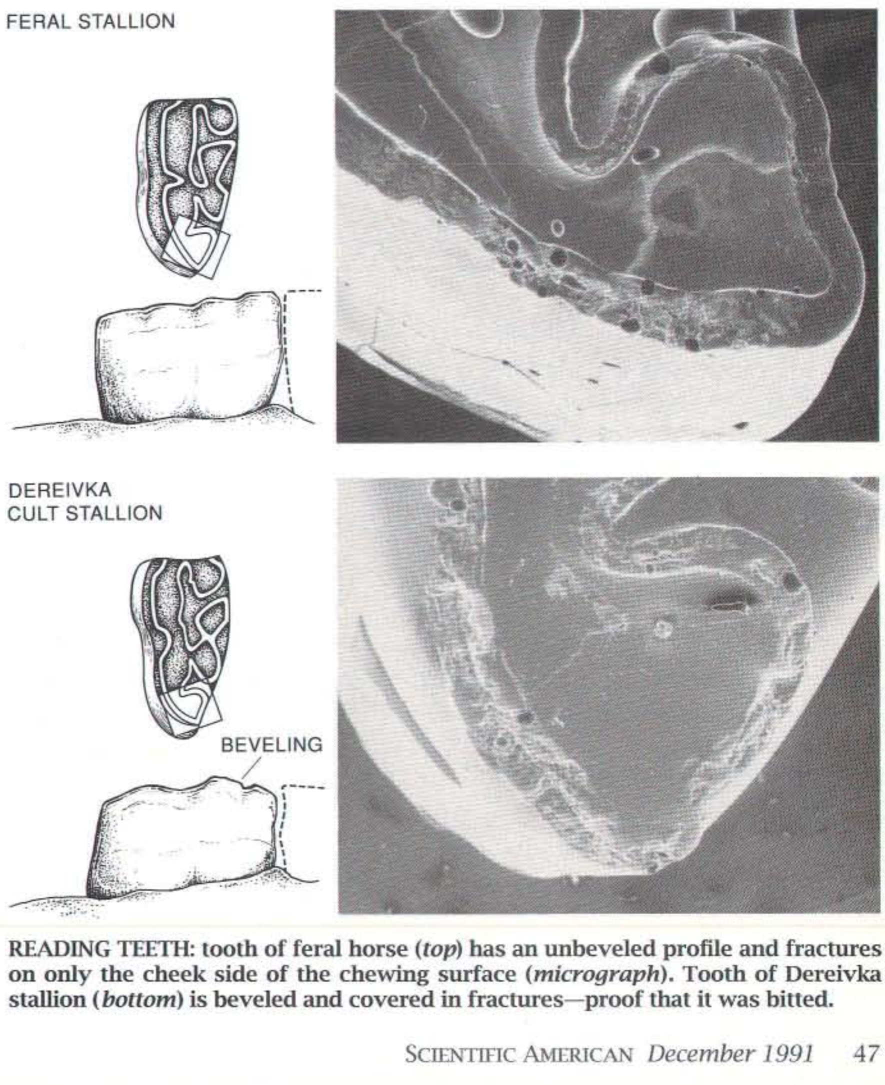
Armed with this knowledge, two of us (Anthony and Brown) went to Kiev at the invitation of the Ukrainian Academy of Sciences. There, together with Telegin and Natalya Belan-Timchenko, an archaeozoologist, we studied the teeth of a wide variety of prehistoric horses. We made high-resolution casts of lower premolars recovered from sites ranging from 25,000 years old to just 1,000 years old. Analysis of the casts in the U.S. established that horse teeth dated earlier than 4000 B.C. showed no beveling or microscopic evidence of bit wear. The Dereivka cult stallion, however, exhibited beveled anterior premolars, with a beveling measurement of 3.5 millimeters, almost exactly the average for our bit-worn control sample and far from the 0.82 average for feral horses.

When the casts of the Dereivka cult stallion premolars were examined under the scanning electron microscope, all the microscopic traits of bit wear were found to be present. Beveling, center-origin spalls and abraded step fractures were in evidence over the entire first cusp. The wear was confined to the beveled area; it did not extend to the rear portion of the same tooth. Moreover, because the Dereivka cult stallion was deposited in a head and hoof ritual, the matching upper jaw was preserved and could be fitted against the lower. No malocclusion could account for any of the wear. The stallion was therefore bitted, which means it must have been guided from behind. Such guidance must be provided by either a rider or the driver of a wheeled vehicle. Five hundred years before the invention of the wheel, such a horse could only have been a mount. It is the first horse known to have been ridden anywhere in the world.

Strangely, none of the four other lower premolar teeth from Dereivka ex-



DEREIVKA STALLION (*top*) is reconstructed as a large-headed animal carrying a rope bit bracketed by antler cheekpieces. A bit in a modern horse (*bottom*) properly rests on the soft tissue, but horses tend to move it onto the teeth.



READING TEETH: tooth of feral horse (*top*) has an unbeveled profile and fractures on only the cheek side of the chewing surface (*micrograph*). Tooth of Dereivka stallion (*bottom*) is beveled and covered in fractures—proof that it was bitted.

hibit clear evidence of bit wear. These teeth were part of the general kitchen refuse at the site and probably came from horses that were eaten. The horse chosen for inclusion in a ritual assemblage with two dogs was the only animal that exhibits clear evidence of usage as a mount.

We sought not only to date the invention of riding but also to ascertain its effects on the society of late Copper Age Europe, roughly from 4000 to 3000 B.C. Several scholars, notably Andrew Sherratt of the University of Oxford's Ashmolean Museum and Sandor Bökönyi of the Hungarian Academy of Sciences, have proposed that extensive social and economic changes were brought on by the use of animals for secondary products, such as wool and dairy foods, and as sources of power for riding and draft. If riding preceded wheeled vehicles, its effects will be distinguishable from those associated with draft.

Recorded cultural responses in the New World provide a model by which to reconstruct the impact of riding in the Ukraine during the Copper Age. Horses may have been among the first tokens of European life to penetrate North America. These horses derived from Spanish stock introduced in the late 17th century by colonists in New Mexico. The horses either escaped or were traded through a chain of indigenous societies to reach the central part of the continent. The tribes there clearly adopted horseback riding long before they encountered guns, European diseases, European traders or other aspects of Western life. The effects of the adoption of riding can therefore be examined in at least partial isolation from other European influences for the period between 1680 and 1750.

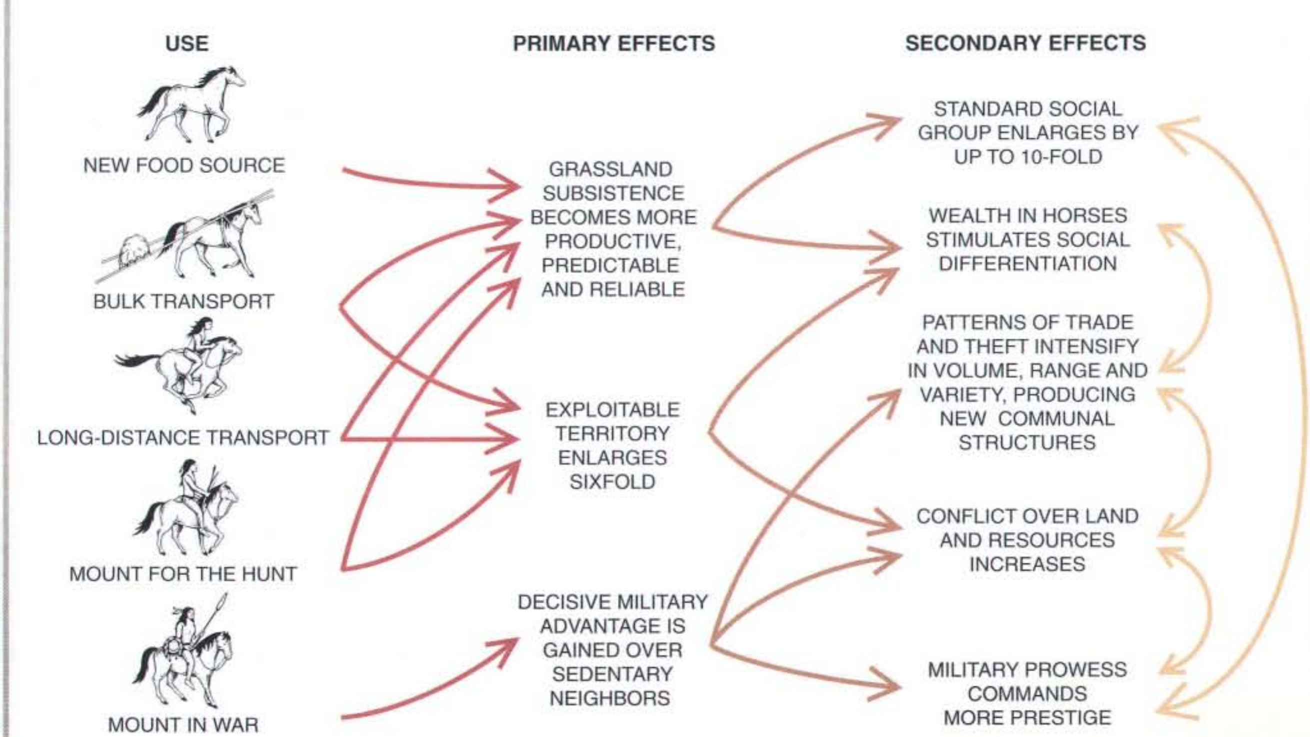
The acquisition of horses wrought a revolution in virtually every aspect of life of the Plains tribes. Riders could move two to three times farther and faster during a day than people on foot. Resources, enemies, allies and markets that had previously been beyond effective reach suddenly became attainable. Subsistence and economic survival in the dry grasslands, an uncertain and risky proposition for pedestrian hunters, became predictable and productive. Sedentary horticultural villagers whose river valley settlements had been the centers of population and economic productivity became vulnerable to lightning raids by mounted enemies who could not be pursued or punished. Many of these villages were abandoned, and their occupants became mounted hunters in self-defense, as happened in the case of the Cheyenne, the Arapaho and the Crow.

Warfare increased in intensity and social importance, both because horses became an easily stolen standard of wealth and because mounted societies redrew ethnic boundaries that had been based on pedestrian travel distances. Trade and exchange systems extended farther, became socially more complex and carried a higher volume of goods (including horses) than had been possible with pedestrian transport. Comparable changes occurred independently in South America.

Similar changes seem to have unfolded in the time of the Sredni Stog culture, which is now well known from excavations at more than 200 sites in the steppe river valleys of the Ukraine. Settlements contained a few lightly built dwellings in which extended family groups might have lived together. They hunted, fished, farmed and herded cattle and sheep—perhaps on horseback. They buried their dead in small cemeteries of 10 to 30 graves, providing most of the deceased with only one or two simple tools as gifts. Some graves, however, contain copper ornaments, shell beads and fine flint implements, suggesting that they harbor members of an incipient elite.

One would expect a newly mounted Sredni Stog population to have entered into radically altered relations with its neighbors, as happened with the Native Americans. In fact, important changes did occur. By the late Sredni Stog period represented at Dereivka, copper ornaments begin to appear in graves in

The Introduction of Horses in North America



numbers and varieties not previously seen east of the Dnieper.

These ornaments clearly derive from the Cucuteni-Tripolye culture, which flourished from about 4500 to 3500 B.C. in the forested uplands between the Dnieper River and the Carpathian Mountains. It had large agricultural towns and many small villages, copper metallurgy, two-story buildings, rituals associating female figurines and grain, and technically sophisticated polychrome ceramic vessels. In addition, copper ornaments of the Cucuteni-Tripolye type and spectrographic composition also begin to appear in cemeteries 900 kilometers east of Dereivka. These ornaments were conveyed as far as Khvalynsk, on the middle Volga, presumably by Sredni Stog middlemen.

Horseback riding, by bringing distant cultures into contact, seems to have stimulated both trade and war. The largest Cucuteni-Tripolye settlements ballooned in size, covering more than 750 acres (300 hectares) and including as many as 1,000 structures. Such unprecedented population concentrations can best be explained as defensive in nature. Moreover, cemeteries resembling those of the Sredni Stog people appear around 3800 B.C. some 600 kilometers to the west of the Dnieper, in eastern Hungary and western Romania. Horseback riding should have led to just such changes: the enrichment of the Sredni Stog culture, the extension of long-distance trade and communication across the grasslands, the defensive concentration of sedentary farming populations and the movement of Sredni Stog groups into resource-rich areas that they had never before been able to exploit.

IMPROPER BIT PLACEMENT is evident in this scene of Afghan horseback riders. The horses have moved the bits to their teeth to relieve pressure on the soft tissue. Such maneuvers leave characteristic marks on the teeth.

It is possible that the first riders spoke a language we would now call proto-Indo-European. Linguists have reconstructed that language, now long extinct, from the evidence of its descendant tongues. These include Sanskrit, Homeric Greek and Latin, as well as such modern languages as English, French, Russian and Persian.

In the past century some archaeologists and linguists have sought the Indo-European homeland in the grasslands of the Ukraine, particularly among the horse-rich remains of the Yamna, a culture that grew partially out of Sredni Stog and expanded across the steppes north of the Black and Caspian seas. James Mallory of Queens College, Belfast, has reasserted the theory of a Ukrainian homeland. Alternatively, other scholars have recently suggested that the Indo-European languages were carried from Anatolia by the expansion of the first farmers during the Neolithic age, long before horses were domesticated [see "The Early History of Indo-European Languages," by Thomas V. Gamkrelidze and V. V. Ivanov; SCIENTIFIC AMERICAN, March 1990].

Even the authors of this article disagree about the original Indo-European homeland. But if the grasslands of the Ukraine did support speakers of some of the early Indo-European dialects—a judgment on which we do agree—then the discovery there of horseback riding near the beginning of the fourth millennium B.C. provides a possible mechanism for their dispersal.

Dispersal to the eastern steppes could have been accomplished through a new economic adaptation based on grassland herding and small-scale agriculture in the river valleys. The deep steppe was a hostile environment; it could not support large human populations prior to the development of horseback riding. In fact, riding helped to transform the vast Eurasian grasslands from a barrier to a conduit of communication and trade.

An eastward dispersion by the first riders would have encountered only small and scattered human resistance. Dispersal to the west would have been much more complex because it would have encountered the well-established agricultural societies of Copper Age Europe. Archaeological data and theoretical models of migration tend to support the theory that such movements took place, first in the east, and then to the west, between 3500 and 3000 B.C.

In all these developments the horse played a critical role, as it would continue to do in human events for the next 5,000 years. But it is now clear that it took a very long time for the custom of riding to diffuse southward into the Middle East. When horses finally did appear there, around 2200 to 2000 B.C., they were used in a role previously played by asses or ass-onager hybrids, as draft animals attached to battle carts. The superior size and speed of horses and perhaps new control methods based on the bit contributed to the refinement of the war chariot by 1800 B.C. It was as a chariot animal that the horse trotted onto the pages of history, two millennia after it had first been broken to the bridle.

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Welcome to the new world

From left, Delta Flight Attendant Bonita Caringola, First Officer Timothy Therrell, Captain Larry Bacon and Flight Attendant Stephanie Allen.

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Chemical Fuels from the Sun

The production of chemical fuels from sunlight offers a form of energy that can be transported and stored, overcoming the limitations of converting solar energy directly to electricity

by Israel Dostrovsky

Because fossil fuels are finite in amount, it is essential to find substitute sources of energy. The search is made even more urgent by the realization that the continued burning of fossil fuels endangers the earth's climate through the emission of carbon dioxide, which as it lingers in the atmosphere is thought to contribute to the warming called the greenhouse effect. The new energy must be renewable, available in amounts large enough to meet global need and environmentally benign. Only one source of such energy is known today: the sun.

At first glance, solar energy appears to be an ideal solution. The amount of solar radiation reaching the surface of the earth totals some 3.9 million exajoules a year. (An exajoule is one billion joules of energy, approximately equivalent to the amount of heat released during the combustion of 22 million tons of oil.) Because the annual consumption of global energy equals 350 exajoules, that amount could be supplied by the solar rays falling on less than 0.1 percent of the earth's surface, harvested with an efficiency of no more than 10 percent. Although the argument is grossly oversimplified, a more careful analysis confirms the basic point: solar energy could easily deliver upward of 450 exajoules a year, even if it were harvested from only a small fraction of the desert areas that receive the most sunlight.

At this point, one must confront two problems. The regions where ample sunshine is available for harvesting do not coincide with the centers of population and industry, where energy demand is greatest. Moreover, solar energy is intermittent.

These problems translate into a need to develop processes for harvesting solar energy on a large scale and converting it into forms suitable for long-term storage and long-range transmission. There are as yet no economically and technologically satisfactory means of achieving those goals, partly because the resources devoted to research in this field are meager. For example, although the International Energy Agency allocates more than 60 percent of its research budget to projects involving nuclear energy, it sets aside less than 4 percent for research on solar energy.

Most of the limited amount of research on solar energy focuses on converting sunlight to electricity, mainly by photovoltaic and thermal methods. In photovoltaic conversion, solid state devices transform solar radiation directly into electricity. (The process supplies power in many space satellites.) In thermal conversion, solar radiation is first transformed into heat, which in turn drives steam turbines and electric generators. The major example of such an application is at Daggett, Calif., where plants based on a design by LUZ International, an Israeli firm, generate about 400 megawatts (million watts) of electricity.

Although electricity constitutes a key means of delivering energy—indeed, it accounts for one third of the world's primary energy—it is not the answer to all the problems involved in the use of solar energy. It cannot be stored conveniently, and transmitting it over long distances gives rise to another set of problems. Therefore, it will not be enough merely to develop solar electricity; additional energy vectors must be sought.

In one approach that meets the requirements of both storage and transportation, sunlight is converted into a chemical. Many chemicals can be piped and stored as gases, liquids or solids and then used as fuels for combustion that generates heat to drive machinery. Some can also be used to generate electricity directly. The production of various chemical fuels through solar-driven processes might solve the impending energy and environmental crises.

Many attempts to produce chemical fuels through solar-driven processes have centered on hydrogen. A light, combustible gas, hydrogen can readily be made by the electrolysis of water. It can also be stored and transmitted over long distances. When burned, hy-

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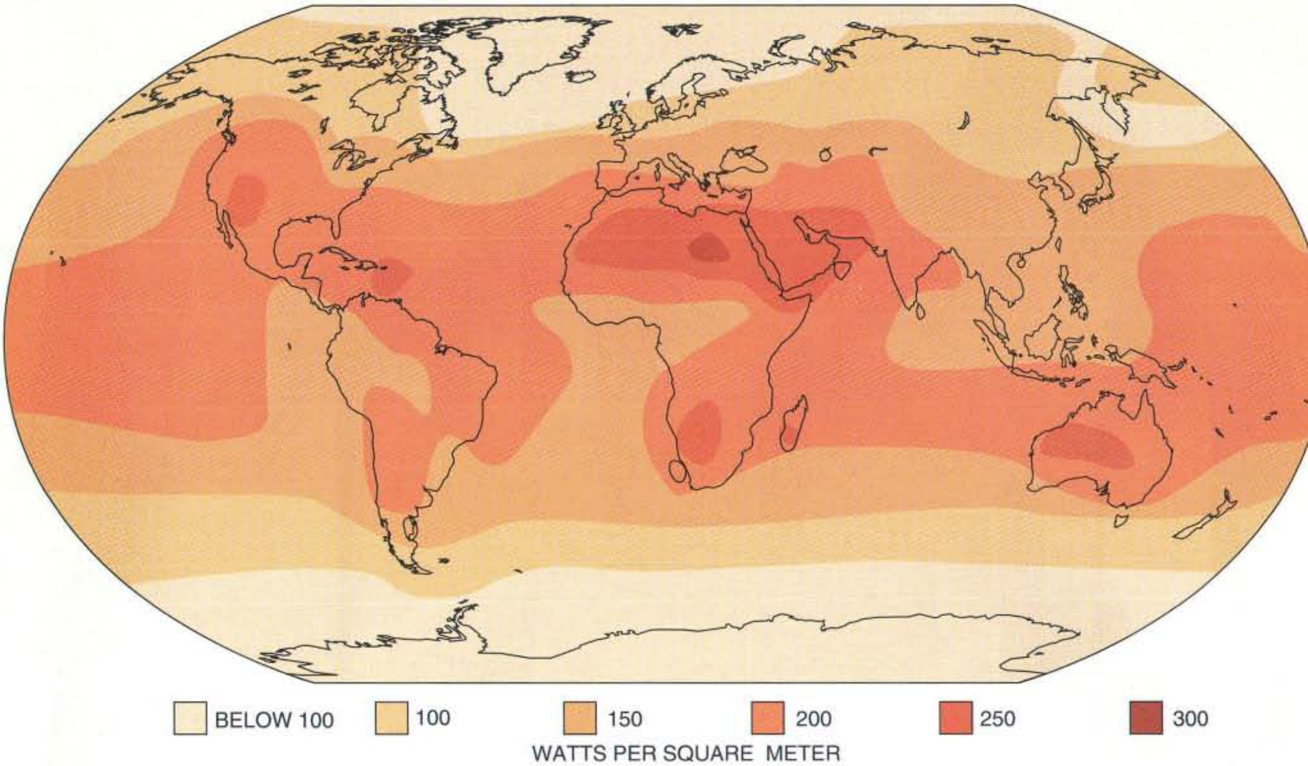
SOLAR TOWER at the Weizmann Institute of Science in Rehovot, Israel, concentrates sunlight to provide heat for driving reactions that yield chemical fuels. Other facilities of this type, which can deliver more than a million watts of power, have been constructed.



AVERAGE AMOUNT OF SUNLIGHT (in watts per square meter) falling on a horizontal area of the earth's surface is shown for a 24-hour period. The abundance of sunshine makes it an obvious source of energy. To be a practical source, however, the energy derived from sunlight must be converted to a form that can be transported and stored.

drogen produces water, and so it is a "zero emission" fuel. But only if the electricity used to make the hydrogen is generated from nonfossil sources such as sunlight, water or wind can the gas be regarded as a truly environmentally benign fuel. Such a system is now being demonstrated in Saudi Arabia. The HYSOLAR project, carried out jointly by Saudi Arabia and Germany, consists of a photovoltaic generator of 350-kilowatt capacity coupled to an electrolysis plant that produces hydrogen.

The overall efficiency of producing hydrogen by electrolysis is calculated by combining the efficiency of generating electricity from the particular renewable source and the efficiency of the electrolysis process itself. Much work in recent years has focused on improving both. Today the efficiency of generating electricity commercially from solar sources is around 12 percent and that of electrolyzing water is about 70 percent, yielding an overall value of approximately 8 percent. As the various projects to develop more efficient solar-generating plants bear fruit, the electrolytic route to solar-produced fuel will become more attractive.

To the extent that hydroelectric power can be viewed as an indirect form of solar energy, the large amounts of hydrogen produced electrolytically in certain countries (notably Norway and Canada) can be regarded as an example of a fuel produced from the sun. In these cases, however, the hydrogen is used by the chemical industry as a raw material for synthesizing ammonia and not as an energy vector.

Producing Hydrogen in Reactions with Sulfur Dioxide

Hydrogen can serve as a chemical fuel. The first step, common to each of the following processes for making it, can be driven by sunlight.

- Hydrogen can be generated in a number of reactions involving sulfur dioxide (SO_2), which is formed during the high-temperature decomposition of sulfuric acid (H_2SO_4):

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/SO_2$$

One way of producing hydrogen with sulfur dioxide, developed by General Atomics in San Diego, Calif., involves the addition of iodine (I_2):

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$$

Subsequent thermal decomposition of the hydrogen iodide (HI) molecules yields hydrogen:

$$2HI \rightarrow H_2 + I_2$$

- A second (electrolytic) process for producing hydrogen was developed at Westinghouse:

$$SO_2 + 2H_2O \rightarrow H_2SO_4 + H_2$$

The advantage of this process is that it requires only an applied voltage of 0.29 volt, much less than the nearly two volts needed to produce hydrogen directly in the electrolysis of water.

- A third process, also electrolytic, was developed at the Ispara Laboratories in Italy; the process involves bromine (Br_2):

$$Br_2 + SO_2 + 2H_2O \rightarrow 2HBr + H_2SO_4$$

The application of 0.62 volt to the hydrogen bromide (HBr) molecules yields hydrogen:

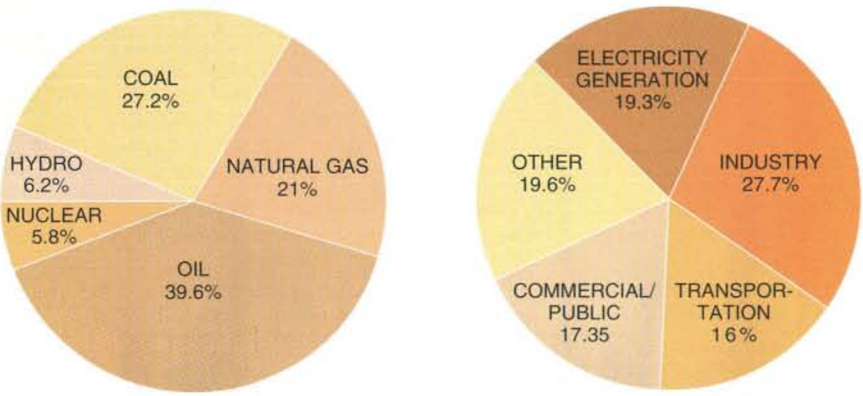
$$2HBr \rightarrow H_2 + Br_2$$

The problems involved in improving the electrolytic path to the large-scale production of hydrogen have prompted a search for other ways to make hydrogen. The search also embraces other chemical systems that do not rely on the intermediate production of electricity.

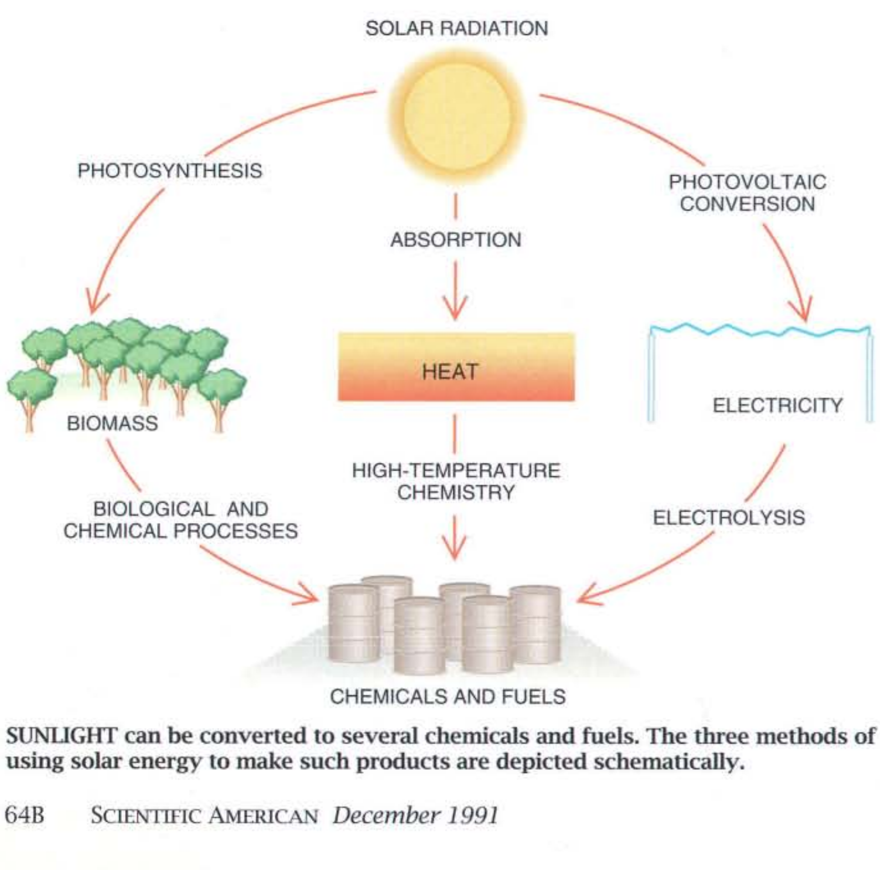
It is theoretically possible to produce hydrogen from water simply by heating the water to a high temperature. At temperatures above 2,000 degrees Celsius, water vapor contains an appreciable amount of hydrogen. Such temperatures are easily within the reach of concentrated solar radiation. The challenge in this process is to keep the hydrogen and the oxygen from recombining as the vapor cools. The two products must be separated while the temperature is still high. The development of a practical separation process suitable for operation at temperatures above 2,000 degrees C is no trivial matter, and research on it is still in progress.

Most hydrogen used in industry today is made from hydrocarbons (coal, natural gas or components of petroleum) with a fossil fuel as the energy source. Such processes are, of course, of little interest in the present context because they use fossil sources. The picture changes, however, when one considers biomass—the general term for plant material—as a substitute for hydrocarbons in some of these processes. Biomass is produced by solar energy through photosynthesis. With biomass as the raw material and solar radiation as the source of energy, one would have a system with the desired characteristics.

This application of solar energy is based on the fact that when organic material, which contains carbon, is heated to a sufficiently high temperature (700 to 900 degrees C) in the absence of air and the presence of steam, it decomposes to yield a gaseous mixture of hydrogen and carbon monoxide. The gas has a low heating value, but the heat is adequate for generating steam or electricity.



GLOBAL PROPORTIONS of the various primary energy sources (*left*) and the major purposes for which they are used (*right*) reveal that electricity accounts for only about a third of the primary energy distributed.



SUNLIGHT can be converted to several chemicals and fuels. The three methods of using solar energy to make such products are depicted schematically.

Even more important for the present discussion, the composition of the gas can be adjusted to make what is known in the industry as synthesis gas, or syngas. It is a mixture of hydrogen and carbon monoxide in a ratio between 2:1 and 3:1, from which, as the name implies, a large variety of materials can be synthesized. Among them are liquid fuels such as methanol and gasoline as well as pure hydrogen.

The current practice is to provide the large amount of heat needed for gasification by burning a considerable fraction of the organic material itself. Using the heat from solar sources, which is fairly simple, would more than double the yield of syngas and any material or fuel produced from it. The carbon dioxide emitted when plant materials are burned or fermented is not added to the atmosphere, however, but recirculated. The process returns to the atmosphere material that had been borrowed from it quite recently.

The gasification process can be applied to carbon-containing materials other than biomass—indeed, to almost all the conventional and unconventional fossil fuels. In such methods the combustion of fuels made from syngas contributes fresh carbon dioxide to the atmosphere and therefore to the greenhouse effect. But here, too, if the sun is the source of heat for gasification and subsequent processing, the effective magnitude of the raw materials will be more than doubled, and the emission of carbon dioxide per unit of fuel consumed will be more than halved.

A particularly interesting application of similar technologies arises in connection with the problems of long-term storage and long-distance transmission of solar energy. In the 1970s workers at Kernforschungsanlage Juelich GmbH (KFA), a nuclear research center in Ger-

many, proposed and tested an entirely new approach for converting nuclear heat into a chemical suitable for commercial and industrial use. The effort took into account the same considerations that apply to solar energy today—namely, the need to transmit the heat from its production site to the consumers and the desire to serve a wider segment of the energy market than is possible through electricity alone.

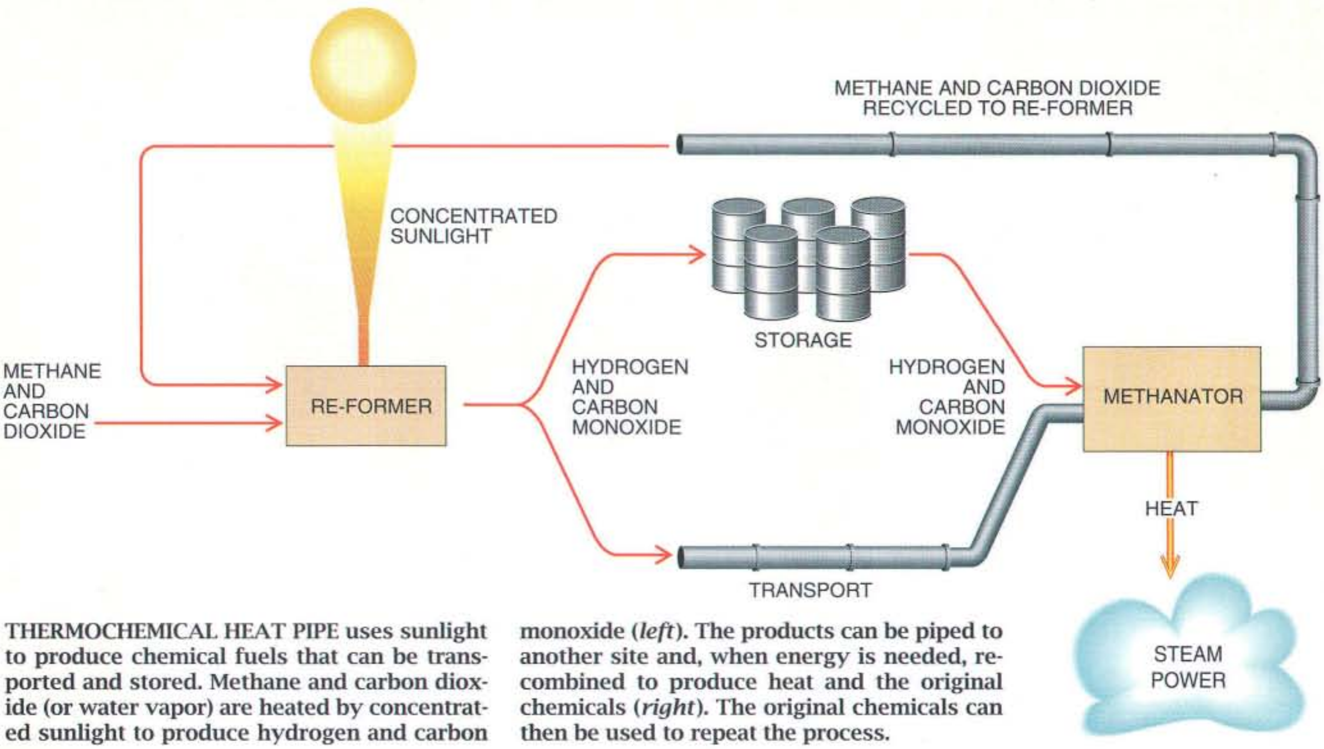
Instead of relying on a single fuel, hydrogen, that would be generated at the nuclear reactor, transmitted to the consumer and then burned, the KFA group sought what is called a reversible chemical system. Such a system would soak up a great deal of heat to yield products that could then be transported over indefinite distances and delivered to consumers. The consumer would reverse the reaction, recovering the heat and regenerating the original chemicals, which would then be returned to the reactor site. The developers called their concept "the thermochemical heat pipe."

Several chemical systems could serve in a thermochemical heat pipe, but they are not all equally convenient. The experimenters at KFA chose what is called the steam re-forming reaction, a process well known in the petrochemical industry. Methane is reacted with steam at a high temperature in the presence of a catalyst to yield a mixture of hydrogen and carbon monoxide—the same syngas described above. The syngas can be stored at ambient temperatures indefinitely and then delivered to the consumer by pipeline.

The consumer causes the mixture to react, again with the help of catalysts. The yield is heat, which is applied to whatever purpose the consumer has in mind, and the original chemicals, which are returned to the re-forming reactor. Trials of the process, using an electric source of heat rather than a nuclear reactor, generated more than 10 million watts of power. (The general retrenchment in the nuclear industry intervened before the workers could test the process in a reactor.)

The concept of the thermochemical heat pipe as applied to solar energy is being explored at the Weizmann Institute of Science in Rehovot, Israel, and the German Aerospace Research Establishment. The work uses the reactions between methane and steam and between methane and carbon dioxide. Both reactions are carried out at temperatures between 900 and 1,000 degrees C on the surface of solid catalysts, which usually contain nickel or rhodium. The high temperature needed

CONCENTRATED SUNLIGHT can be produced by a solar furnace (*top*) or a solar dish (*bottom*). The furnace intensifies terrestrial radiation up to 10,000-fold and is capable of delivering tens of thousands of watts of power. The dish yields up to 150,000 watts. This furnace is at the Weizmann Institute; the dish, located near Stuttgart, is operated by the German Aerospace Research Establishment.



THERMOCHEMICAL HEAT PIPE uses sunlight to produce chemical fuels that can be transported and stored. Methane and carbon dioxide (or water vapor) are heated by concentrated sunlight to produce hydrogen and carbon monoxide (*left*). The products can be piped to another site and, when energy is needed, recombined to produce heat and the original chemicals (*right*). The original chemicals can then be used to repeat the process.

to drive the re-formers is produced by concentrated sunlight. Because it is a closed-cycle process, no materials are consumed, and no by-products are emitted to the atmosphere. The system has a great asset: its three functions—capturing solar energy and converting it to chemical energy, storing the energy, and using it ultimately to generate electricity or provide heat for an industrial process—can be carried out in different locations, each optimal for the particular function.

The concentrated solar radiation needed for all these processes can readily be obtained by means of mirrors arranged in various configurations. The technologies include the solar furnace, the dish concentrator and the solar tower. One's choice depends on the amount of power sought: solar furnaces can provide power at several tens of kilowatts, dishes in the range of hundreds of kilowatts and towers in the thousands of kilowatts. Commercial solar towers aim at power levels of hundreds of megawatts; the experimental towers now operating are rated at from three to five megawatts.

Whatever the means of concentrating sunlight, perhaps the most elegant way of delivering solar energy to drive the reactions is to illuminate the catalysts directly with concentrated sunlight. One way passes the light into the chemical reactor (the re-former) through a window, which would keep the contents out of contact with the atmosphere. The major problem with this technique is the size of the window that would be required for a large-scale operation.

Another approach, which avoids the need for a window but pays the penalty of a less direct way of introducing the solar energy to the reaction mixture, encloses the mixture in tubes and heats them from the outside with solar radiation. The approach has been tested successfully at the Schaefer Solar Furnace Facility of the Weizmann Institute. A scaled-up version with a power of 400 kilowatts is being constructed at the Kay Family Solar Spire there.

To protect the tubes from overheating while ensuring that the delivery of energy is uniform and easily controlled, a separate heat-transfer medium couples the solar radiation to the chemical reaction. In an approach first proposed at Sandia National Laboratories in Albuquerque, N. M., vapors of boiling sodium, heated by concentrated sunlight, bathe the reaction tubes and keep them at a constant temperature. A successful test of this idea was carried out jointly by a team from Sandia and the Weizmann Institute at the Schaefer Solar Furnace.

Heat can also be transferred by air, which can be circulated through a jacket surrounding the tubes. Several designs of such a system for transferring heat have been proposed and are now being tested in Israel and Spain.

Other concepts for heating air to high temperature by means of solar energy are being developed in several laboratories, notably in Israel, Germany, Spain and the U.S. All the approaches involve making air flow over extended surfaces that are heated with concentrated solar radiation. The surfaces can be wire grids, ceramic foams, ceramic honeycombs or suspended particles. If the operation is to be pressurized, windows are necessary. They are not necessary if air at atmospheric pressure can be used, in which case the design can be much simpler.

Much is at stake here. The successful development of these processes would create an ample supply of clean energy for as long as the sun shines.

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The Brush Turkey

This Australian bird is one of a family that constructs mounds in which to incubate its eggs. The process requires remarkable adaptations of both egg and hatchling

by Roger S. Seymour

In Australia and the surrounding Indo-Pacific islands lives a group of birds that is unusual even by the exotic standards of the fauna of this region. These creatures—informally called mound builders—do not sit on their eggs to warm them. Instead they deposit their eggs in places where external sources provide heat for incubation. Some tropical island species bury their eggs in sand warmed by the sun or by geothermal activity, whereas others construct heaps of plant litter in which energy from microbial decomposition keeps the temperature high.

The 19 species in this family of birds, called the Megapodiidae because of their exceptionally large feet, are no more involved in raising their young than they are in incubating them. Unlike the attentive parents of, say, a young finch or thrush, megapode parents do not care for or feed their newly hatched offspring.

To achieve early independence, megapode eggs and hatchlings are equipped with special features. A unique design allows the egg to develop in the mound—an environment that would kill the embryos of most birds. And megapode chicks emerge not only with a respiratory capability different from that of most birds but with precocious strength and foraging ability.

Recent studies of one of the true mound builders living in tropical and subtropical forests, the Australian brush turkey (*Alectura lathami*), have provided insight into the characteristics of the megapode mound, egg and offspring. With help from my colleagues David and Carol M. Vleck, David Bradford, David T. Booth and Dominic Williams, I have examined the regulation of mound temperature, the gas exchange mechanisms of the eggs and of the mound microorganisms, the energetics of embryonic development and the details of the striking biological transition that occurs during hatching. These studies continue a vein of research initiated 35 years ago, when the breeding biology of the mallee fowl (*Leipoa ocellata*), one of the most famous of the compost assemblers, was first investigated [see "Incubator Birds," by H. J. Frith; SCIENTIFIC AMERICAN, August 1959].

The distinctive ritual of brush turkey parenting begins in the winter months. At that time, the male collects litter—including leaves, small branches, twigs and moss—and kicks it backward into thickets or under a forest canopy until he has assembled a mound about one meter high and five meters in diameter. The brush turkey then mixes the material and breaks it up by digging holes in the top of the heap and refilling them. In a few weeks, the mound consists of a relatively fine, friable compost covered with a layer of larger sticks and twigs.

The decomposition of the litter is brought about chiefly by fungi, which produce the heat that will incubate the eggs. After an initial period during which mound temperature varies because of the biological phases of the

ROGER S. SEYMOUR is senior lecturer in zoology at the University of Adelaide, South Australia. In 1972, after completing his Ph.D. in zoology at the University of California, Los Angeles, Seymour moved to Australia, where he has studied the respiratory and cardiovascular physiology of unusual animals ever since. His subjects have included sea snakes, crocodiles as well as the eggs of terrestrially breeding frogs and mound-building birds. In the February 1991 issue of *Scientific American*, Seymour and Peggy D. Rismiller described the reproductive biology of an egg-laying mammal, the echidna.

BRUSH TURKEY inhabits the tropical and subtropical forests of Australia. The adult male (shown here with an identification tag on his shoulder) builds mounds to incubate his mate's eggs.

microorganisms, the temperature at a depth of about 60 centimeters, where the eggs will be placed, stabilizes around 33 degrees Celsius. The incubation temperature remains constant, within a range of one or two degrees, throughout the breeding season.

While the male constructs the mound, the female forages, nourishing herself for the delivery of her eggs. When the mound is ready, she can lay an egg every three days or so for five to seven months. Each egg is laid at the bottom of a wedge-shaped trench dug by the female. Because the mound serves as a continuous incubator, some eggs develop and hatch while others are being laid—as many as 16 eggs can exist in a mound at any one time.

By constructing artificial mounds and manipulating natural ones, we have been able to determine the factors leading to temperature stability. First, the size of the mound has proved crucial. On Kangaroo Island off South Australia, for instance, brush turkeys build mounds that weigh about 6.8 metric tons and are 12 cubic meters in volume. Such mounds have great thermal inertia and remain virtually independent of daily changes in external temperature.

The mound also acts as a thermostat. The core temperature depends on the balance between the rate of microbial heat production and the rate of heat loss from the mound. We measured the rate of microbial oxygen consumption, an indicator of the rate of heat production, and found that it increases exponentially with mound temperature. Heat loss also increases with mound temperature, but in a steeper

fashion. When these two increases are plotted as lines, they intersect. The point where they cross marks the stable temperature at which heat loss equals production.

Interestingly, the mound temperature always tends to fall or rise toward this equilibrium temperature. At core temperatures below equilibrium, heat production is greater than heat loss, and the mound warms. If the mound is cooled when opened by the male to test the temperature or by the female to lay an egg, for instance, it will warm up again after it is reconstructed. On the other hand, if the mound temperature is above equilibrium, it cools because heat loss exceeds heat production.

Although mound homeothermy will keep a temperature stable, the appropriate incubation temperature has to be established by the birds. A brush turkey tests temperature by inserting its one-inch-long beak into the mound material during excavations. If the core temperature is too low, the bird adds a small amount of fresh litter to the mound. This action supplies nutrients to the microorganisms and raises the level of heat production. It also slightly enlarges the mound, thereby reducing the rate of heat loss. This process is very precise: one centimeter of fresh material added to the mound can increase the core temperature by about one and a half degrees C.

Once the mound is constructed and the temperature stabilized, the birds do not need to do much work to maintain the temperature. The level is so constant, in fact, that some unattended mounds sustain temperatures favorable for incubation for over six months.

INCUBATION MOUND is composed of dry forest litter that affords plenty of air space. Average mounds on Kangaroo Island off South Australia weigh 6.8 metric tons and measure 12 cubic meters (about 423 cubic feet) in volume.

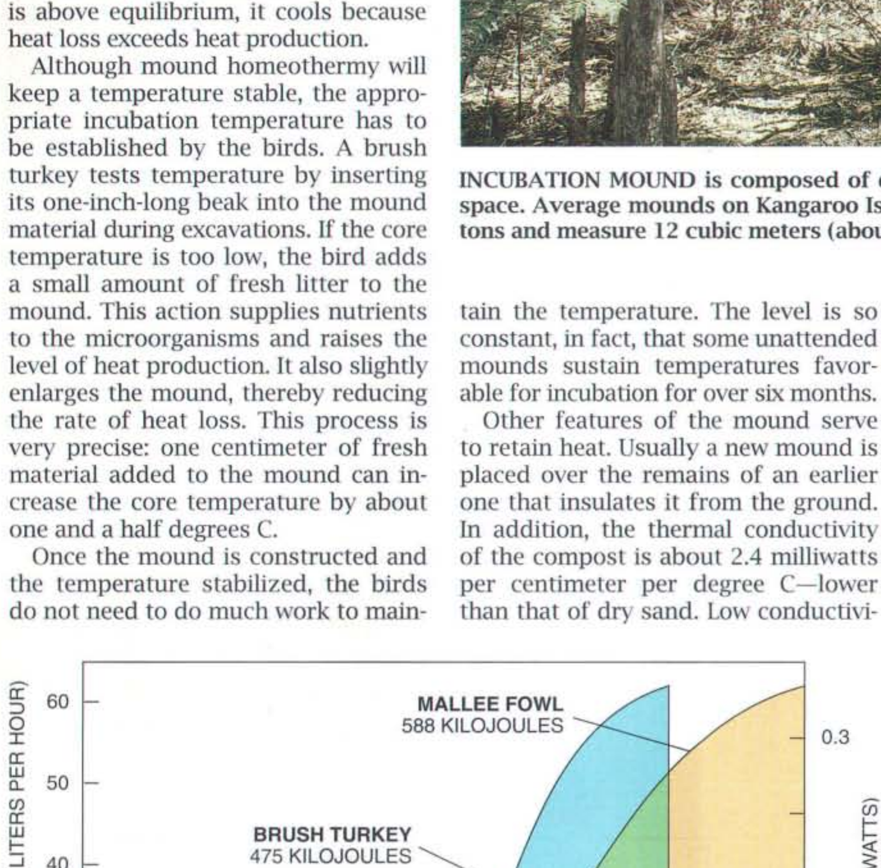
Other features of the mound serve to retain heat. Usually a new mound is placed over the remains of an earlier one that insulates it from the ground. In addition, the thermal conductivity of the compost is about 2.4 milliwatts per centimeter per degree C—lower than that of dry sand. Low conductivity, which results from the dryness of the mound (it contains only 30 milliliters of water per 100 grams of solid material), prevents heat loss.

Even if the mound were wetter, incubation temperature could be maintained by higher rates of heat production and heat loss. This process would necessitate the collection of more leaves and twigs. As it is, mounds produce a minimal amount of heat, about 100 to 200 watts, and the energy in the litter lasts several months.

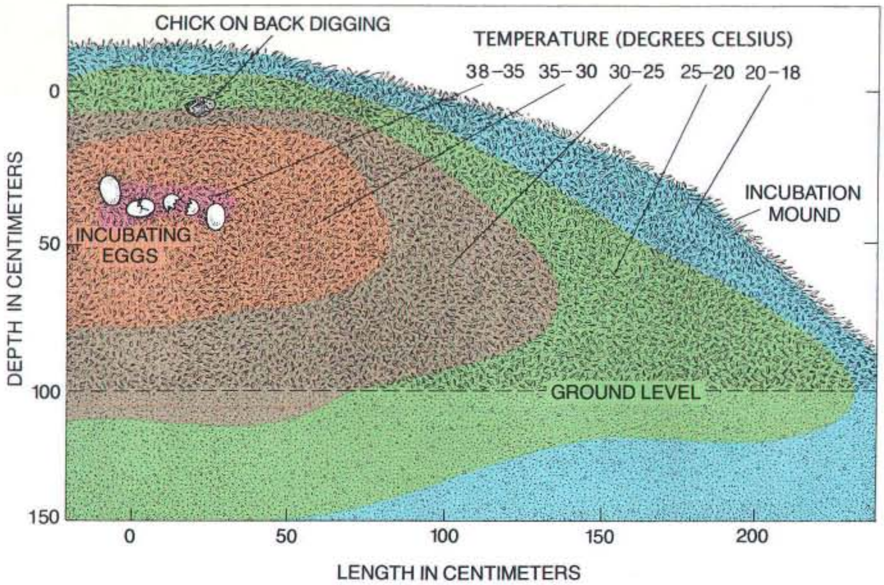
Brush turkeys can also turn the weather to their advantage. More than 50 years ago the eminent Australian naturalist David H. Fleay suggested that the birds could control the entry of rain by altering the mound shape, keeping it round on top when the material was moist and creating a crater when water was needed. Our observations support this idea.

The precise regulation of gas exchange parallels the finely tuned temperature regulation of the mound. Some researchers have reported that fermentation generates the microbial heat in the mound. Our work, however, points to aerobic respiration. The microorganisms consume oxygen at a rate of about 20 liters per hour, 60 times the rate of consumption by all the eggs in the mound. Oxygen is supplied as the atmosphere diffuses through holes between the litter particles. These spaces occupy about 70 percent of the mound's volume.

Maintaining a low water content maximizes the air space and ensures



ENERGY REQUIREMENT is greater for embryos that must fend for themselves after hatching, such as the mallee fowl (*right*) and brush turkey (*center*), than for galliform birds (*left*) whose parents care for them. The areas defined by each curve represent the embryos' energy requirement in kilojoules. The curves indicate oxygen consumption and a related measure, metabolic rate, from the time when the egg is laid through the time when the chick emerges.



CROSS SECTION of a mound shows that the warmest region occurs at a depth of about 60 centimeters. Respiration by microorganisms and the embryos reduces the oxygen levels and increases the carbon dioxide levels around the eggs.

that oxygen levels near the eggs do not drop too low and that carbon dioxide levels do not rise too high. Nevertheless, the oxygen content of the mound decreases from 21 percent at the surface to about 17 percent near the eggs; carbon dioxide levels rise from 0 to 4 percent.

These gas levels would be stressful to the brush turkey embryo were it not for the special architecture of the megapode egg. The shell of the brush turkey egg is about half as thick as the shell of a comparable, normal avian egg—relative to the size of the bird. The thin shell increases permeability by decreasing the distance that gas must travel as it diffuses.

David Booth and I also discovered that the inside of the shell is dissolved by the embryo during development. This action removes the narrowest, most restrictive part of the shell's pores, which taper as they approach the inner wall. The result is that the shell's gas permeability is three times greater than that of most bird eggs [see "How Bird Eggs Breathe," by Hermann Rahn, Amos Ar and Charles V. Paganelli; SCIENTIFIC AMERICAN, February 1979]. This increase in permeability almost entirely offsets the abnormal gas levels in the mound and exposes the embryo inside the shell to oxygen and carbon dioxide levels well within the range experienced by embryos of most other birds.

Having a thin shell, however, could put the brush turkey embryo at risk in other ways. For example, egg mortality among birds poisoned by DDT has shown that a sitting parent can easily break a thin shell [see "Pesticides and the Reproduction of Birds," by David B. Peakall; SCIENTIFIC AMERICAN, April 1970]. But the mound impressively protects megapode eggs from this kind of breakage. We have even stood on brush turkey eggs buried only 10 centimeters below without breaking them.

Brush turkey eggs also differ from normal bird eggs with regard to water conservation. The late Hermann Rahn of the State University of New York at Buffalo, Amos Ar of Tel-Aviv University and their associates have shown that during incubation, most bird eggs lose an average of 18 percent of their initial weight through evaporation. This water is part of a pool present in the egg at laying in addition to metabolic water formed by the catabolism, or breakdown, primarily of lipids in the yolk. The water budget is such that very little liquid water is lost during hatching.

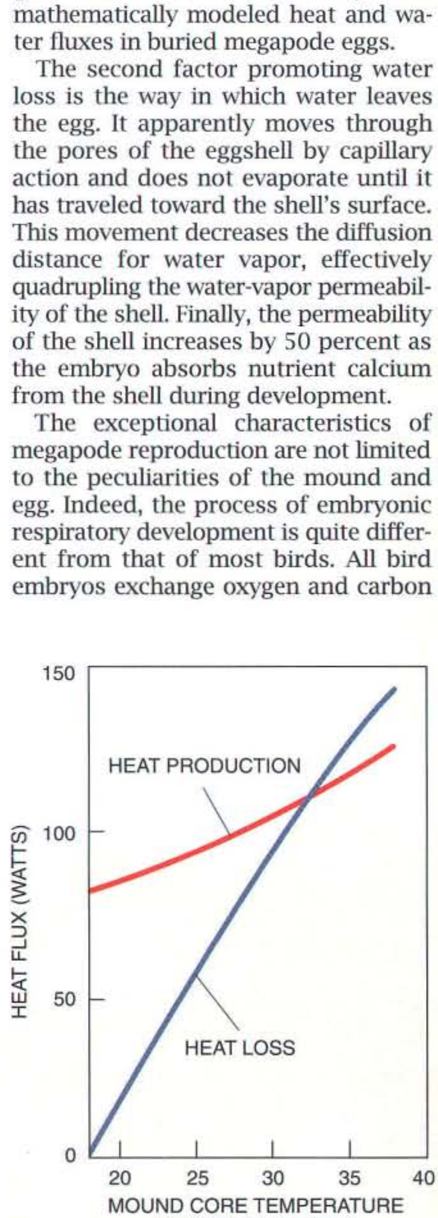
In contrast, brush turkey eggs are incubated in high humidity. They lose only 9.5 percent of their water by evaporation despite an incubation period of 49 days—about 20 days longer than other birds of the same size. Moreover, high rates of metabolism during the extended incubation period produce a large amount of metabolic water, equivalent to about 7 percent of the initial egg mass. Thus, brush turkey eggs lose about 25 milliliters of excess water when they emerge.

It was surprising to us that the eggs evaporate as much water as they do, because the relative humidity in the mound is greater than 99 percent. We measured the permeability of the eggshell, expecting to find that an egg would lose about 0.1 percent of its initial weight. Instead we found that it lost nearly 10 percent. The large discrepancy resulted from three factors that are, again, specific to megapode eggs.

Most important is the metabolic heat produced by the embryo in a highly insulated environment. During incubation, this heat progressively raises egg temperature from 33 to 38 degrees C, thereby increasing the water-vapor pressure gradient across the shell 40-fold. Our measurements were confirmed by Ralph A. Ackerman and Richard C. Seagrave of Iowa State University, who mathematically modeled heat and water fluxes in buried megapode eggs.

The second factor promoting water loss is the way in which water leaves the egg. It apparently moves through the pores of the eggshell by capillary action and does not evaporate until it has traveled toward the shell's surface. This movement decreases the diffusion distance for water vapor, effectively quadrupling the water-vapor permeability of the shell. Finally, the permeability of the shell increases by 50 percent as the embryo absorbs nutrient calcium from the shell during development.

The exceptional characteristics of megapode reproduction are not limited to the peculiarities of the mound and egg. Indeed, the process of embryonic respiratory development is quite different from that of most birds. All bird embryos exchange oxygen and carbon



EQUILIBRIUM TEMPERATURE in mound is reached at the point of intersection, when heat production equals heat loss.

dioxide with the environment through a special respiratory organ called the chorioallantois. This double membrane is produced by the embryo and grows from the umbilical region toward the shell. By the time incubation is about half complete, the chorioallantois surrounds the embryo, which continually supplies it with blood. The embryo finishes development inside this sole gas exchange organ, a situation rather like living inside one's own lung.

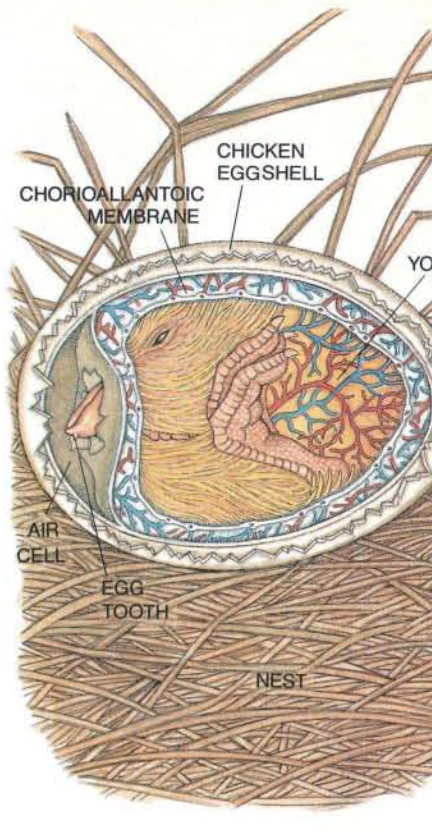
For this reason, the developing bird encounters a potential problem at the time of hatching. Breaking out of the egg requires considerable effort and therefore a good amount of oxygen. Yet in breaking out of the egg, the hatchling must destroy its only source of oxygen: the chorioallantois. The solution that most birds use is to begin developing the lungs as effective gas exchangers well before hatching.

During incubation, the space in the egg left by evaporating water is replaced by air. The gas collects in a compartment that usually appears at the blunt end of the egg, where the membranes just inside the shell split apart to enclose the air. This air cell, apparent in hard-boiled chicken eggs, increases in size as water is lost during the course of development. The pocket of air is essential in normal eggs because, near the end of incubation, the chick thrusts its beak into this chamber and begins ventilating its lungs. This activity is called internal pipping; it is followed several hours later by external pipping, when the chick breaks the shell at one point and begins to breathe the outside air. A few hours later the chick hatches.

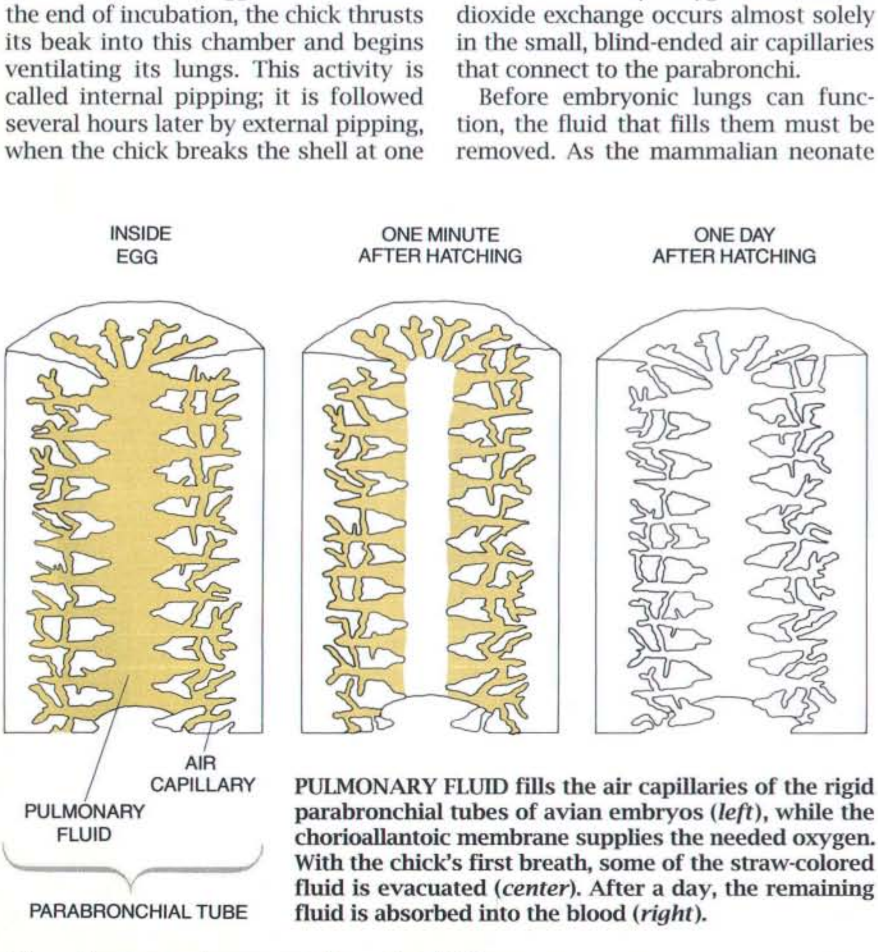
Pulmonary respiration develops slowly, over the course of a day, as A.H.J. Visschedijk of the University of Utrecht has shown in his studies of chickens. Meanwhile the circulation to the chorioallantois is gradually reduced until, at hatching, it has practically ceased to function. The chick can now break through the chorioallantois without danger of blood loss. The development of pulmonary function allows the bird enough oxygen to satisfy its metabolic requirements during hatching.

Aeration in the lungs in neonate birds is a slow process because of the structure of the avian lung. Effective lung function depends on getting air to the gas exchange part of the lung. But unlike mammalian neonates that can expand their lungs and inspire enough gas into the alveoli to satisfy oxygen requirements at birth, birds cannot expand and contract their lungs. Their lungs are made up of a series of tubules, called parabronchi, that reside in pulmonary cavities of fixed volume [see "How Birds Breathe," by Knut Schmidt-Nielsen; SCIENTIFIC AMERICAN, December 1971]. Air is forced through the parabronchi from several expandable air sacs that act like bellows within the bird's body. Oxygen and carbon dioxide exchange occurs almost solely in the small, blind-ended air capillaries that connect to the parabronchi.

Before embryonic lungs can function, the fluid that fills them must be removed. As the mammalian neonate passes through the birth canal, emerges and takes its first gasps, much of this fluid is removed within minutes or seconds by changes in lung volume. Although some fluid remains in the alveoli of the lungs, enough has been lost to satisfy the oxygen needs of the resting newborn.



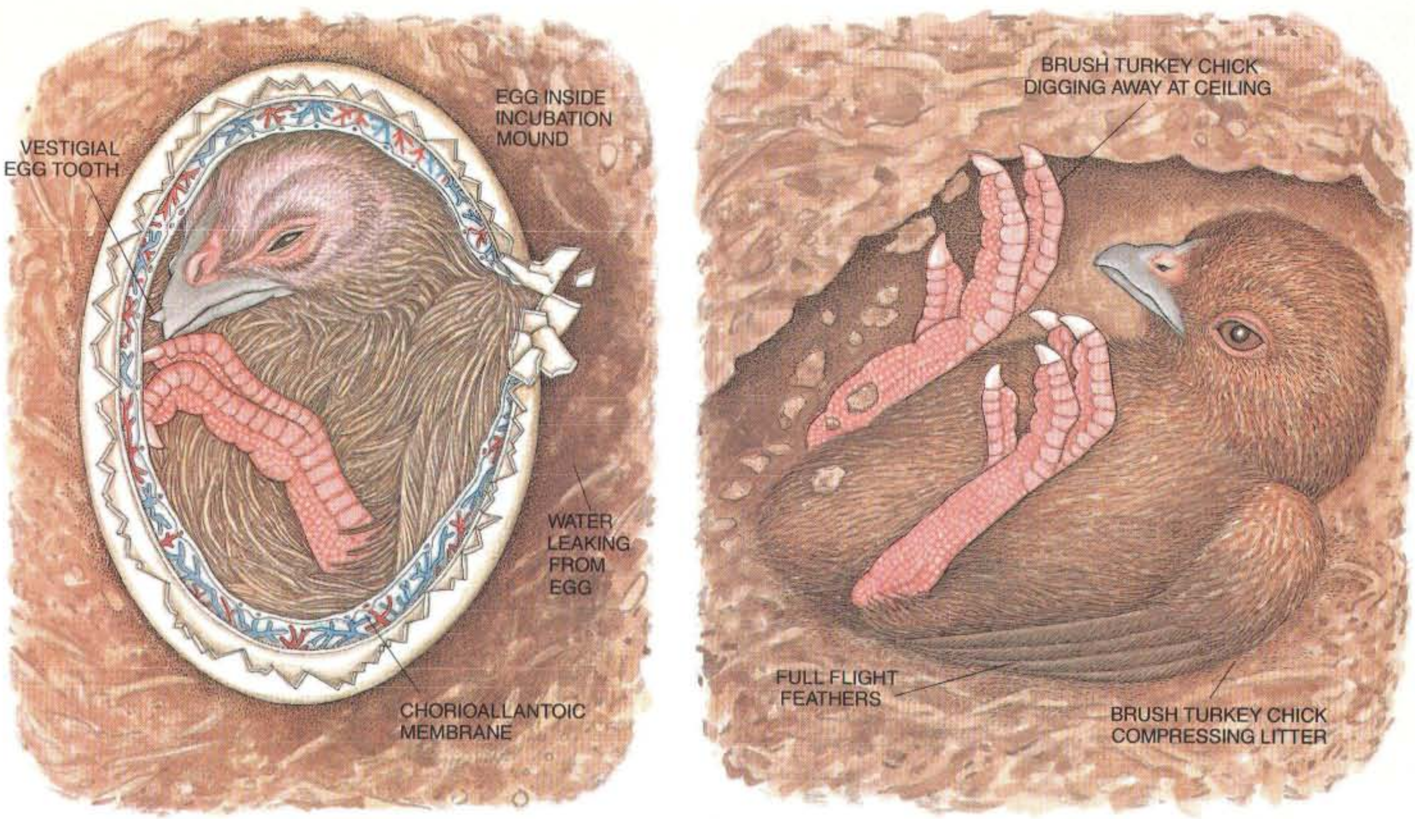
CHICKEN EMBRYO breathes in the air cell after piercing the chorioallantois.



PULMONARY FLUID fills the air capillaries of the rigid parabronchial tubes of avian embryos (*left*), while the chorioallantoic membrane supplies the needed oxygen. With the chick's first breath, some of the straw-colored fluid is evacuated (*center*). After a day, the remaining fluid is absorbed into the blood (*right*).

In birds, on the other hand, the fluid in the constant-volume lung can be removed only through absorption into the pulmonary bloodstream, a process taking many hours. The lungs of chickens, for instance, require more than 24 hours of progressive aeration before hatching. At that time, air volume reaches 44 percent of total lung volume, about two thirds of the adult value.

Brush turkeys, and probably other megapodes as well, provide exceptions to this rule of respiratory development. There is practically no overlap in the change from chorioallantoic to pulmonary respiration, a slow transition that had been thought to be universal among birds. In brush turkeys the lung contains absolutely no air before hatching occurs. The shell membranes of megapode eggs are not adapted to form an air cell at one end, so a chick has no place to begin breathing inside the egg.



HATCHING BRUSH TURKEY breaks free of the shell by pushing with its shoulders (*left*). The egg's shell is thinner than that of most birds' eggs and contains no air cell. The young digs out of the mound (*right*) using its large feet.

Instead the chick begins to breathe just after hatching. The young bird breaks free by pushing against the shell with its legs and back until the shell suddenly cracks. The chick's feet rip long slits through the chorioallantois, and the blood flow in it stops immediately as smooth muscles contract and the chick starts breathing.

Megapode chicks can hatch successfully without developing pulmonary function because hatching is relatively easy for them. Unlike birds such as ostriches, which may take two days to escape from a thick shell, a megapode chick can quickly and easily break through its abnormally thin container. Apparently, sufficient gas exchange exists after the first few breaths to keep the birds alive—but probably not enough exchange for immediate exertion. Indeed, brush turkeys rest for several hours after hatching while their lungs become aerated.

Although breaking out of the egg requires little energy, digging out of the mound is very demanding. Brush turkeys hatch about 60 centimeters beneath the surface, and they must free themselves without any help from the parent. We have observed chicks digging upward through plastic columns of mound material in the laboratory. The chick turns on its back and uses its feet to scrape the roof of the cavity; it lets the debris fall around its body and then compresses the material with its back. Bouts of digging are often broken by long periods during which the chick breathes heavily. Emergence takes about two and a half days. Measurements of oxygen consumption during this time indicate that the cost in energy is about a third of that used during the preceding 49 days of incubation.

Lack of parental care necessitates the chick's complete independence. The megapode hatchlings have been described as superprecocious: they hatch with full primary feathers, and some can even fly on their first day out. Booth showed in my laboratory that brush turkeys and mallee fowl do not need to be brooded, because they can maintain a stable body temperature in environments ranging from five to 45 degrees C immediately after their plumage dries.

The exceptional maturity at hatching is associated with a large investment of energy in the eggs and a long incubation. Brush turkey adults, which weigh about 1,800 grams (about four pounds), would be expected to lay 60-gram (2.1-ounce) eggs if they were like some other species of their order, the Galliformes. Their eggs, however, weigh 180 grams, one tenth of the adult body weight. Females require two to five days to form these large eggs, rather than the one to two days expected in most other birds. The energy-rich yolk occupies 50 percent of the egg, in contrast to 40 percent in other precocious species and about 20 percent in nonprecocious species such as parrots and pelicans. Our measurements of embryonic oxygen consumption indicate that the total amount of energy used in development is about four times that expected from eggs of similarly sized gallinaceous birds [*see bottom illustration on page 70*].

At first glance, burying eggs and leaving them to incubate seems purely reptilian in nature. In fact, a few crocodilians, such as the estuarine crocodile (*Crocodylus porosus*), build mounds of vegetation and deposit their clutches inside. But although megapode mound building was once considered a primitive process, it is now thought to be derived from usual avian incubation behavior.

The main evidence for this idea is that megapode chicks have both an egg tooth and hatching muscles on the back of the neck—although they are not

YOUNG BRUSH TURKEY emerges with full flight feathers, ready to fend for itself. This hatchling and an unhatched egg were found during a mound excavation.

used. The egg tooth is a calcareous cone on the tip of the bill that helps most chicks pierce the shell. The muscles pull the head back during hatching and force the egg tooth through the shell. In megapode chicks, these structures appear to be vestiges from ancestral birds, which presumably required them while breaking free of thick-shelled eggs incubated under the parent.

The Australian naturalist H. J. Frith suggested a possible evolutionary sequence leading from ground-nesting tropical birds that sat on their eggs to birds that built mounds. According to his theory, the warm tropical environment where ancestral megapodes arose probably allowed the parents considerable time away from the nest. While away, the parent may have covered the eggs with soil or litter to conceal them and to help retain heat. If the birds chose sites naturally heated by the sun or volcanism, they could remain away from the eggs for much longer periods, a trend that would culminate in complete abandonment.

The eggs, however, needed to be supplied with enough energy and nutrients to produce a chick that would be capable of survival without parental care. This requirement selected for large, energy-rich eggs. With freedom from the nest, the females extended the foraging time that could provide the energy and nutrients needed to produce such eggs.

As the birds invaded cooler regions such as the highlands of oceanic islands or the temperate forests of Australia, more litter may have been needed to keep the egg warm during the parents' absence. It is easy to imagine that the decomposition of litter eventually provided some heat to the eggs and that this opened the door for further invasion of cooler habitats. As far as we can determine, there are no indigenous predators that break apart the mound and devour the eggs.

Once successful incubation did not require parental supervision, the adults were free to produce large numbers of completely independent young. In one season, with plentiful resources, female brush turkeys can lay as many as 50 eggs, weighing a total of nine kilograms. Because the incubation time is so long and the laying interval is three days, a 1,800-gram bird could not possibly incubate even the standard 16 eggs in one mound by sitting on them.

High fecundity is probably the principal selective advantage of megapode incubation behavior, but sometimes it is apparently matched by high mortality in the first year of life. Although we know little about the natural history of hatchling brush turkeys, David Priddel of the National Parks and Wildlife Service of New South Wales has recorded high mortality of mallee fowl chicks caused by starvation.

As far as we can determine, however, brush turkeys are thriving in tropical forests and, in fact, have become somewhat of a nuisance. To avoid the chore of building mounds, some of them are reportedly claiming man-made compost heaps as their own. Perhaps for the brush turkey, such commandeering represents the next evolutionary step.

FURTHER READING

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Sophie Germain

An extraordinary mathematician, she struggled against the prejudices of 19th-century French society to produce enduring work in number theory and the theory of elasticity

by Amy Dahan Dalmédico

Can you name a famous female mathematician? I would wager that you cannot. But you should first think of Hypatia of Alexandria. Her contemporaries praised her work in mathematics, although none of it survives. Perhaps her writings were destroyed by the Christian monks who stoned her to death in 415 for her pagan beliefs. More than 1,300 years later there was the Marquise de Châtelet, who translated Sir Isaac Newton's *Principia Mathematica* into French. In 1750 the Italian scholar Maria Gaetana Agnesi, known for her achievements in differential calculus, became the first woman professor of mathematics.

Like Hypatia, the Marquise and Agnesi, Sophie Germain fought fiercely against the prejudices of her family, friends and co-workers to become an accomplished mathematician. Germain possessed exceptional talents, great ambition and an undistracted passion for science. She taught herself mathematics and physics and produced original work in number theory and the theory of elasticity. Despite these accomplishments, Germain has still not received the recognition she deserves.

Sophie Germain was born in Paris on April 1, 1776, a decade before the French Revolution and a century after the Scientific Revolution. The laws of Newton governed the cosmos, while the decrees of Louis XVI ruled France. Germain supported political change and advanced the cause of mathematics and physics, and she would fight most fiercely to break the barriers that kept women out of science.

Her father, Ambroise-François Germain, focused his attention on the French Revolution. Ambroise belonged to the society of liberal, educated bourgeoisie. The Germain family had been merchants for generations, and they were comfortable financially. To protect his interests, Ambroise served as an elected deputy of the third estate of the Constituent Assembly of 1789.

At the age of 13, Sophie was described as shy and awkward. She felt her family was obsessed with money and politics, and she took refuge in her father's library, where her intellectual development began. She tutored herself in mathematics by reading every book she could find. Just as she could not understand her parents' interest in politics, they could not grasp her love of mathematics. They thought her interest was astonishing for her age and incongruous with her sex.

The Italian mathematician G. T. Libri-Carrucci—who later became Germain's friend—recounted how the young woman overcame her parents' insistence that she abandon her interest in mathematics. While the family slept, she would study by candlelight. On winter nights when the ink froze in the well, she would read, wrapped in blankets. Her determination outlasted the will of her parents. And despite her "strange" interests, her father supported her financially throughout her life. Germain neither married nor obtained a professional position that could sustain her.

Germain enjoyed reading about Archimedes in the *History of Mathematics,* by Jean-Étienne Montucla. She identified with Archimedes' struggle to continue his research in the midst of the Roman invasion of Syracuse. She progressed from Étienne Bezout's treatise on arithmetic to the works of Newton and the Swiss mathematician Leonhard Euler.

Relatives, friends and educators paid little attention to the interests and talents of young Sophie. They saw little purpose in engaging the mind of a girl from a middle-class family.

Germain was 19 when the École Polytechnique was founded. She obtained the lecture notes for many courses, including analysis taught by Joseph-Louis Lagrange and chemistry by Antoine-François Fourcroy. During one session, Lagrange asked his students to evaluate the course. Fearing her opinions would be ignored, Germain submitted her comments under the name of a former student, Antoine-August Le Blanc. (It is not known whether Le Blanc gave his consent.)

Germain's education in science was extremely unusual for a woman of her social status. During the 18th century, science was taught to some aristocratic women through popularized accounts written specifically for them. The books revealed only enough science to allow a woman to chat about the subject at social events. Francesco Algarotti wrote one of the most notable books of this genre: *Sir Isaac Newton's Philosophy Explain'd for the Use of the Ladies.*

Algarotti believed women were interested only in gallantry and love, and so he tried to teach physics while catering to those interests. His book revolves around a dialogue between a marquise and her interlocutor. In one scene the interlocutor teaches the inverse square law. He explains that the force of gravity—or the intensity of light—decreases in proportion to the inverse square of the distance between the object and the observer. The marquise replies that she is familiar with the concept. "I cannot help thinking... that this proportion in the squares of the distances of

SOPHIE GERMAIN produced great works in mathematics, but as a middle-class woman living at the time of the French Revolution, she never received the recognition she deserved from fellow scientists. A statue of her now stands in the courtyard of the École Sophie Germain, a lycée in Paris.

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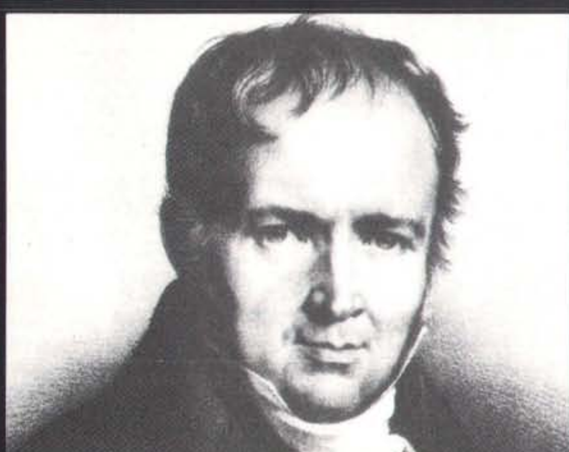
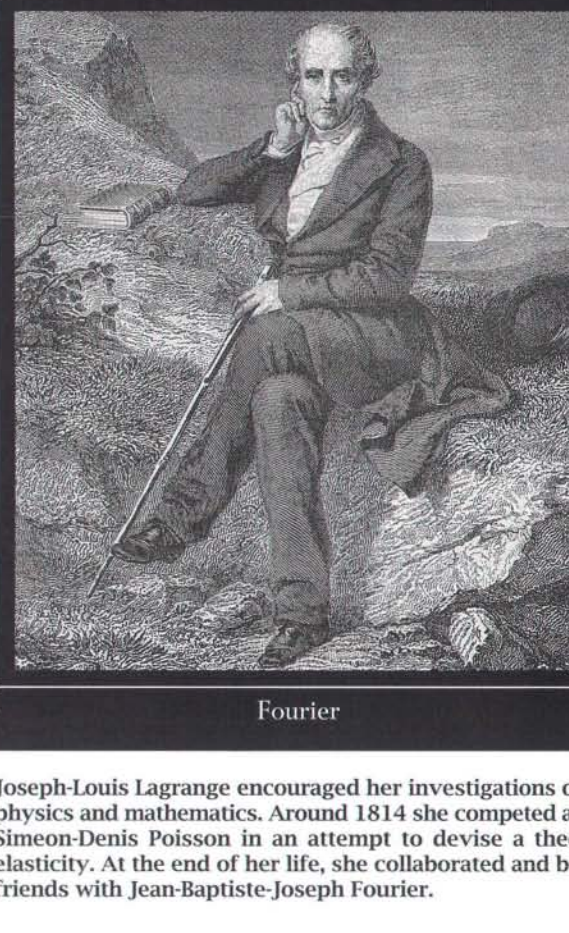
Gauss

Lagrange



Poisson



Fourier

FRIENDS AND RIVALS of Sophie Germain were some of the most famous mathematicians and physicists of the 19th century, but most of the scientific community regarded her with indifference. Early in her career Germain exchanged many letters about number theory with Carl Friedrich Gauss. Joseph-Louis Lagrange encouraged her investigations of both physics and mathematics. Around 1814 she competed against Simeon-Denis Poisson in an attempt to devise a theory of elasticity. At the end of her life, she collaborated and became friends with Jean-Baptiste-Joseph Fourier.

places . . . is observed even in love. Thus after eight days absence love becomes sixty four times less than it was the first day." Such digressions fill the pages of the book and obscure the few passages that explain physics rigorously.

Germain had no tolerance for such frivolous literature. She was enraged by Joseph-Jérôme Lalande when he implied that she would not be able to understand the work of Pierre-Simon Laplace until she read Lalande's book *Astronomy for Ladies.* Germain made it known publicly that she would not speak to Lalande again.

Her education was disorganized and haphazard. She was granted meetings with Lagrange and several other scientists. Some challenged her with small problems. But Germain yearned for professional training. She was never given the opportunity.

Germain was isolated not only from the community of male scientists but also from the society of educated women. Her social status did not allow her to converse with aristocratic women. Furthermore, she was not related to a male scientist who could introduce her ideas on her behalf—a strategy that worked for the Duchess of Gotta and Madame Lalande.

Germain may also have contributed to her own isolation. She avoided social encounters simply because of modesty and shyness. She believed, like the encyclopedists whom she had read, that her contributions to science would stand the tests of time and social prejudice on their own.

Germain was left outside the scientific community during a period when it was attracting more members, organizing more institutions and encouraging more collaboration than ever be-

fore. She was no longer studying in the cold, but she would have to climb an icy wall to gain recognition for her work.

At the turn of the 19th century, Germain found some of her greatest opportunities in the field of number theory. Her first professional contacts, Lagrange and Adrien-Marie Legendre, were both very interested in the subject and encouraged her to learn it.

Over several years she developed a thorough understanding of the complicated methods presented in *Disquisitiones Arithmeticae* by the German mathematician Carl Friedrich Gauss. Excited by the book, Germain wrote him a dozen letters between 1804 and 1809. She signed the letters with the pseudonym "Le Blanc" because she feared "the ridicule associated with being a female scholar."

In her first letter to Gauss, Germain discusses Fermat's equation, namely,

$$x^n + y^n = z^n$$

where x, y, z and n are integers. Pierre de Fermat believed he could prove that the equation cannot be solved if n is greater than 2. To this day, this conjecture, which is known as Fermat's last theorem, has not been proved [see "Fermat's Last Theorem," by Harold M. Edwards; SCIENTIFIC AMERICAN, October 1978].

Germain discovered that Fermat's equation cannot be solved if n is equal to $p-1$, where p is a prime number of the form $8k + 7$. (For example, if k equals 2, then p is a prime number, namely, 23, and n equals 22.) Germain explained her proof to Gauss and remarked: "Unfortunately, the depth of my intellect does not equal the voracity of my appetite, and I feel a kind of temerity in troubling a man of genius when I have no other claim to his attention than an admiration necessarily shared by all his readers."

Gauss responded: "I am delighted that arithmetic has found in you so able a friend. Your new proof...is very fine, although it seems to be an isolated case and cannot be applied to other numbers."

In 1806 Germain relayed a message to Gauss through Joseph-Marie Pernety, an army commander who was her friend. Germain was concerned for Gauss's safety as Napoleon I had recently conquered most of Prussia. She told Pernety she feared Gauss might suffer the same fate as Archimedes, who was killed by the Romans. Pernety sent a messenger to report that Gauss was well but that the mathematician did not know Sophie Germain. In her next letter to Gauss, Germain—alias Le Blanc—revealed her true identity.

Gauss was surprised and delighted. "A woman because of her sex and our prejudices encounters infinitely more obstacles than a man in familiarizing herself with complicated problems. Yet when she overcomes these barriers and penetrates that which is most hidden, she undoubtedly possesses the most noble courage, extraordinary talent and superior genius." Gauss was sincere in his praise of Germain as revealed in letters to the German astronomer Heinrich W. M. Olbers.

In 1808 Germain wrote to Gauss, describing what would be her most brilliant work in number theory. Germain proved that if x, y and z are integers and if

$$x^5 + y^5 = z^5$$

then either x, y or z must be divisible by 5. Germain's theorem is a major step toward proving Fermat's last theorem for the case where n equals 5.

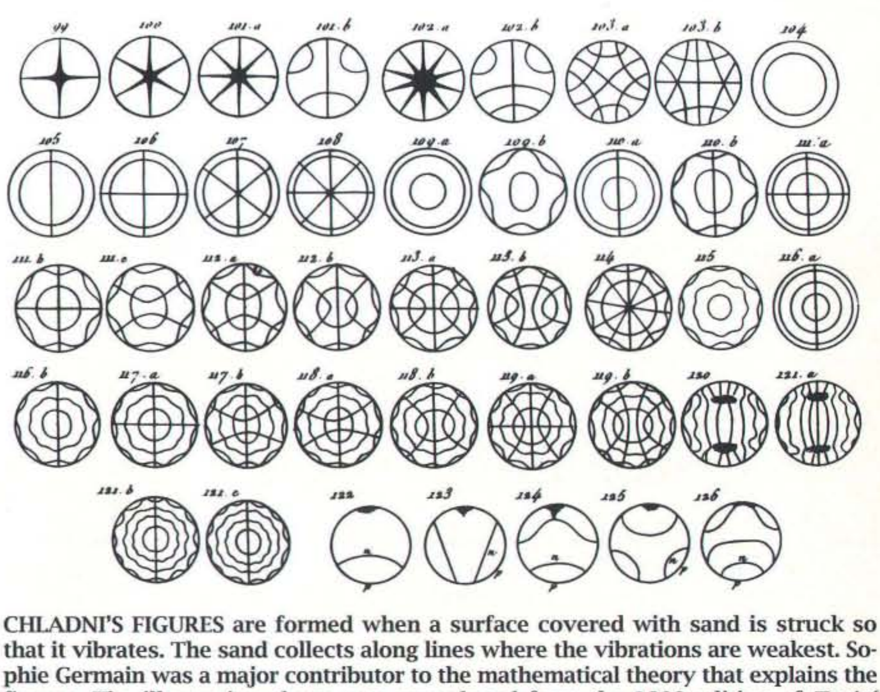
Gauss never commented on Germain's theorem. He had recently become professor of astronomy at the University of Göttingen, and he set aside his work in number theory. He became consumed with professional and personal problems.

For the most part, Germain's theorem remained unknown. In 1823 Legendre mentions it in a paper in which he describes his proof of Fermat's last theorem for the case where n is 5. (In 1676 Bernard Frénicle de Bessy had proved the case where n is 4; in 1738 Euler had found the solution for n equals 3.) Germain's theorem was the most important result related to Fermat's last theorem from 1738, until the contributions of Ernst E. Kummer in 1840.

Sophie Germain depended on Gauss to guide her research in number theory. When their correspondence ceased, she searched for new problems and new mentors. In 1809 she found a challenge that would inspire some of her finest work. She strove to explain the classic experiments of Ernst F. F. Chladni, a German physicist who was investigating the vibrations of elastic plates.

In his experiments, Chladni poured fine sand on top of a glass plate. He then rubbed a bow against the plate, causing a vibration. The sand bounced away from regions that vibrated and collected at "nodes," places that remained still. Within seconds, the plate was covered with a series of sandy curves. The patterns were symmetric and spectacular: circles, stars and other geometric figures [*see illustration below*]. The character of the pattern depended on the shape of the plate, the position of the supports and the frequency of the vibration.

On a visit to Paris in 1808, Chladni presented his experiments before 60 mathematicians and physicists of the First Class of the Institute of France, a section of the French Academy of Science. Chladni's demonstrations so as-



CHLADNI'S FIGURES are formed when a surface covered with sand is struck so that it vibrates. The sand collects along lines where the vibrations are weakest. Sophie Germain was a major contributor to the mathematical theory that explains the figures. The illustration above was reproduced from the 1809 edition of *Traité d'Acoustique*, by Ernst F. F. Chladni.

tounded the scientists that they asked him to repeat his demonstration before Napoleon. The Emperor was impressed, and he agreed that the First Class should award a medal of one kilogram of gold to anyone who could devise a theory that explained Chladni's experiments. In 1809 the First Class announced the contest and set a deadline of two years for all entrees.

Germain seized this opportunity. For more than a decade, she would attempt to devise a theory of elasticity. She would compete or collaborate with some of the most eminent mathematicians and physicists. She would feel proud to contribute to a subject that explored the frontier of 19th-century science.

Nevertheless, Germain would remain a stranger in the world of science. Etiquette demanded that she obtain a letter of invitation each time she wished to visit an institution. Her host was required to provide transportation and escorts. These formalities restricted her freedom to discuss topics with scientists. Consequently, she had many difficulties in leaping from the field of number theory to the subject of elasticity.

To prepare herself for a theory of vibrations, she turned to texts such as Lagrange's *Analytical Mechanics* and Euler's essays on the vibrations of elastic rods. Germain tried to explain the behavior of elastic plates by applying the methods that Euler had used. Euler had suggested that a force applied to a rod is counteracted by an internal force of elasticity. He claimed that the force of elasticity at any point along the rod is proportional to the curvature of the rod. Euler's essays inspired Germain to invent a similar hypothesis. She proposed that at any point on a surface, the force of elasticity is proportional to the sum of the major curvatures of the surface at that point. The major curvatures are the maximum and minimum values of curvature out of all the curves formed when planes cut through the surface perpendicularly.

In 1811 Germain was the only entrant in the contest, but her work did not win the award. She had not derived her hypothesis from principles of physics nor could she have done so at the time, because she lacked knowledge of analysis and the calculus of variations.

But her work did spark new insights. Lagrange, who was one of the judges of the contest, corrected the errors in Germain's calculations and came up with an equation that he believed might describe Chladni's patterns. Lagrange deduced that if z is the amplitude of the vibration and if z is small, then

$$\frac{d^2z}{dt^2} + k^2 \left[\frac{d^4z}{dx^2} + \frac{d^4z}{dy^2} + \frac{d^4z}{dx^2dy^2} \right] = 0$$

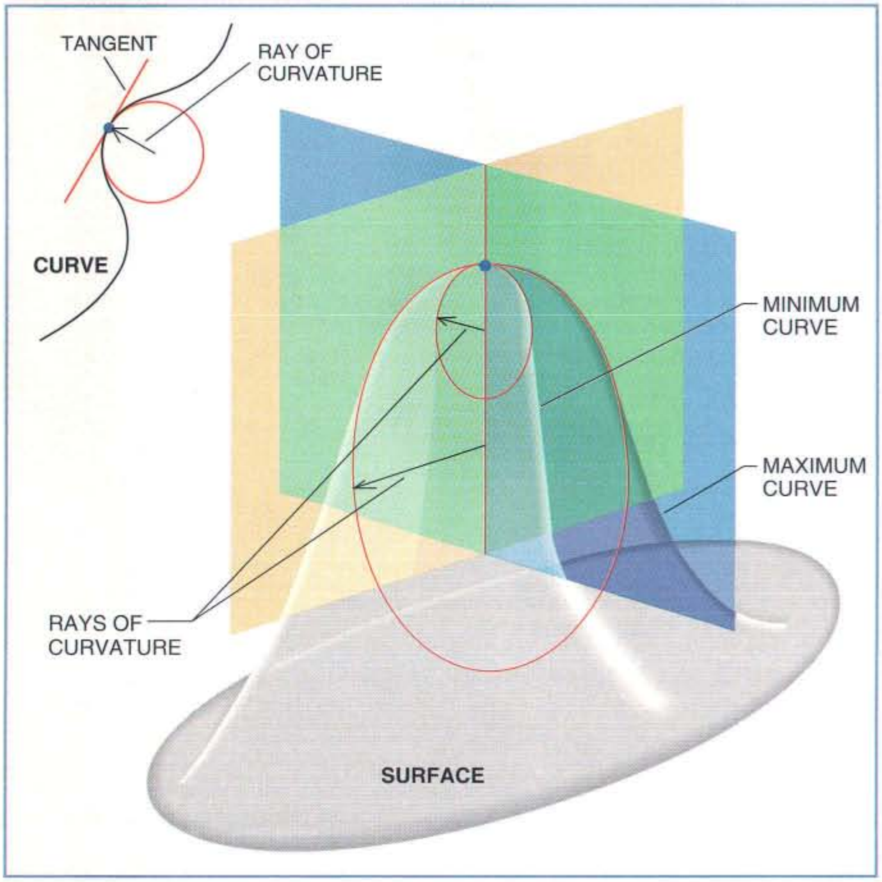
where t is time, k is a constant and x and y represent points on the surface.

In 1811 the First Class extended the contest deadline by two years, and again Germain submitted the only entry. She demonstrated that Lagrange's equation did yield Chladni's patterns in several simple cases. But she could not devise a satisfactory derivation of Lagrange's equation from physical principles. For this work, she received honorable mention from the First Class.

At about the same time, Simeon-Denis Poisson began to invade Germain's intellectual territory. He would become her chief rival. In stark contrast to Germain's experience, Poisson approached the subject of elasticity with all the resources available to a 19th-century scientist.

Poisson entered the École Polytechnique in 1798 at the age of 17. Lagrange and Laplace noticed his talents in problem solving and abstraction. With the support of Laplace, Poisson moved easily through the ranks of academia. He became a professor at the École Polytechnique and at the Faculty of Sciences in Paris. He frequented the famous Société d'Arcueil, where some of the most distinguished scientists came to discuss and perform novel experiments. Laplace and Claude-Louis Berthollet led the society, and Poisson was its mathematical adviser. In 1812 Poisson, who had entered the heart of the scientific community, was elected to the First Class.

Poisson sought to explain the vibrations of elastic plates by applying the Newtonian model of physics. He began with the idea that a plate consists of molecules that mutually repel and attract one another. He then made what may have seemed like a set of plausible assumptions. He derived a very complicated formula and, by simplifying it, arrived at Lagrange's equation. By mod-



CONCEPT OF CURVATURE was fundamental to Sophie Germain's work on the theory of elasticity. A curve can be closely approximated, at any point, by a circle that shares a tangent with the curve at that point. The curvature is equal to the inverse of the length of the ray that runs from the center of the circle to the point of tangency. For a surface, the curvature at a point is related to the curvature of the curves formed by the intersection of the surface with planes perpendicular to the surface at that point. Out of all such curves, the one that has the greatest curvature and the one that has the least are known as principal curves.

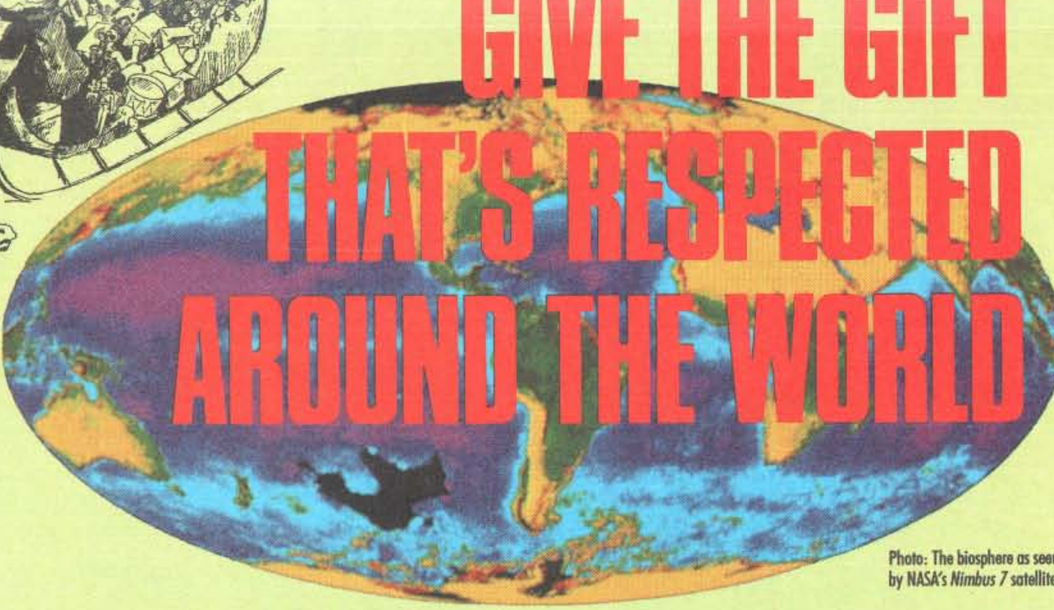


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Photo: The biosphere as seen by NASA's *Nimbus 7* satellite.

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ern standards, Poisson's assumptions seem absurd, and he was successful in his derivation of Lagrange's equation only because he had been aware of the work of Germain and Lagrange.

In 1814 Poisson published his article on elastic plates. As a member of the First Class, he was ineligible to compete for the prize. But many of his peers believed Poisson had found a theory that explained the physical mechanisms of Chladni's patterns. The prize was not retired, however.

"I have greatly regretted not knowing the paper of Poisson," Germain wrote in 1815 in an essay on elasticity. "I spent time, precious to me, waiting for the publication." In this paper, she attacked Poisson's approach while trying to propose her own explanation. Germain postulated that the force of elasticity is proportional to the applied force, which in turn is related to the deformation of the surface. The force at one point is proportional to the sum of all curvatures through that point. She then showed that the sum of all curvatures is related to the sum of the maximum and minimum curvatures. Finally, she derived Lagrange's equation from the sum of major curvatures.

This essay became Germain's third entry in the contest whose judges were, at that time, Legendre, Laplace and Poisson. They could not accept her postulate that the effect—the deformation—is necessarily proportional to the cause, that is, the applied force. Indeed, decades would pass before an explanation was found. With this reservation, the judges awarded Germain the prize of the First Class. Germain did not attend the award ceremony. Perhaps she thought the judges did not fully appreciate her work, or perhaps she simply did not want to appear in public.

To Germain, the award represented formal recognition of her competence. It gave her authority and confidence. But the scientific community did not show the respect that seemed due to her. Poisson sent a laconic and formal acknowledgment of her work. He avoided any serious discussion with her and ignored her in public. A few years earlier she had viewed herself as an inferior novice in the company of giants. Now she felt no admiration for her colleagues.

SALONS of the 19th century were perhaps the only institutions where it was socially acceptable for women to participate in conversations about the great scientific discoveries and debates of the day. Sophie Germain struggled to gain admittance to scientific institutions and societies where she could discuss her theories seriously. The above scene, which was painted by Isidore Pils in 1849, depicts a salon of the period in Strasbourg.

Her spirits were soon lifted by a new friendship with Jean-Baptiste-Joseph Fourier. Germain and Fourier both suffered in their careers because of their rivalry with Poisson, and they shared a dislike of him. Through Fourier's efforts, Germain began participating in the activities of the Parisian scientific community. She attended sessions of the Academy of Sciences and was the first woman who was not the wife of a member to do so.

In the 1820s she began an ambitious research project to refine her proofs and contributions to number theory. She and Legendre worked on the project as equal collaborators. She also published a review of her theory of elasticity. She became interested in various scientific fields and socialized with the intellectual elite. Her curiosity and her charm were appreciated by all.

Although Germain certainly produced work worthy of a degree, she never received one. In 1830 Gauss failed to persuade the University of Göttingen to award her the title of *doctor honoris causa*.

After battling breast cancer for two years, Sophie Germain died on June 27, 1831, at the age of 55. She is described on her death certificate as *rentere*, which translates as "a person of private means" but which has the connotation of "an independent woman."

Before her death, she outlined a philosophical essay, which she never finished. It was published posthumously as *General Considerations on Sciences and Letters*. In the essay, she tried to identify the intellectual process in all human activities. She believed the intellectual universe is filled with analogies. The human spirit recognizes these analogies, which then leads to the discovery of natural phenomena and the laws of the universe. We should recognize the analogies between the life of Sophie Germain and our own, and they should lead us to strive for excellence in the face of prejudice.

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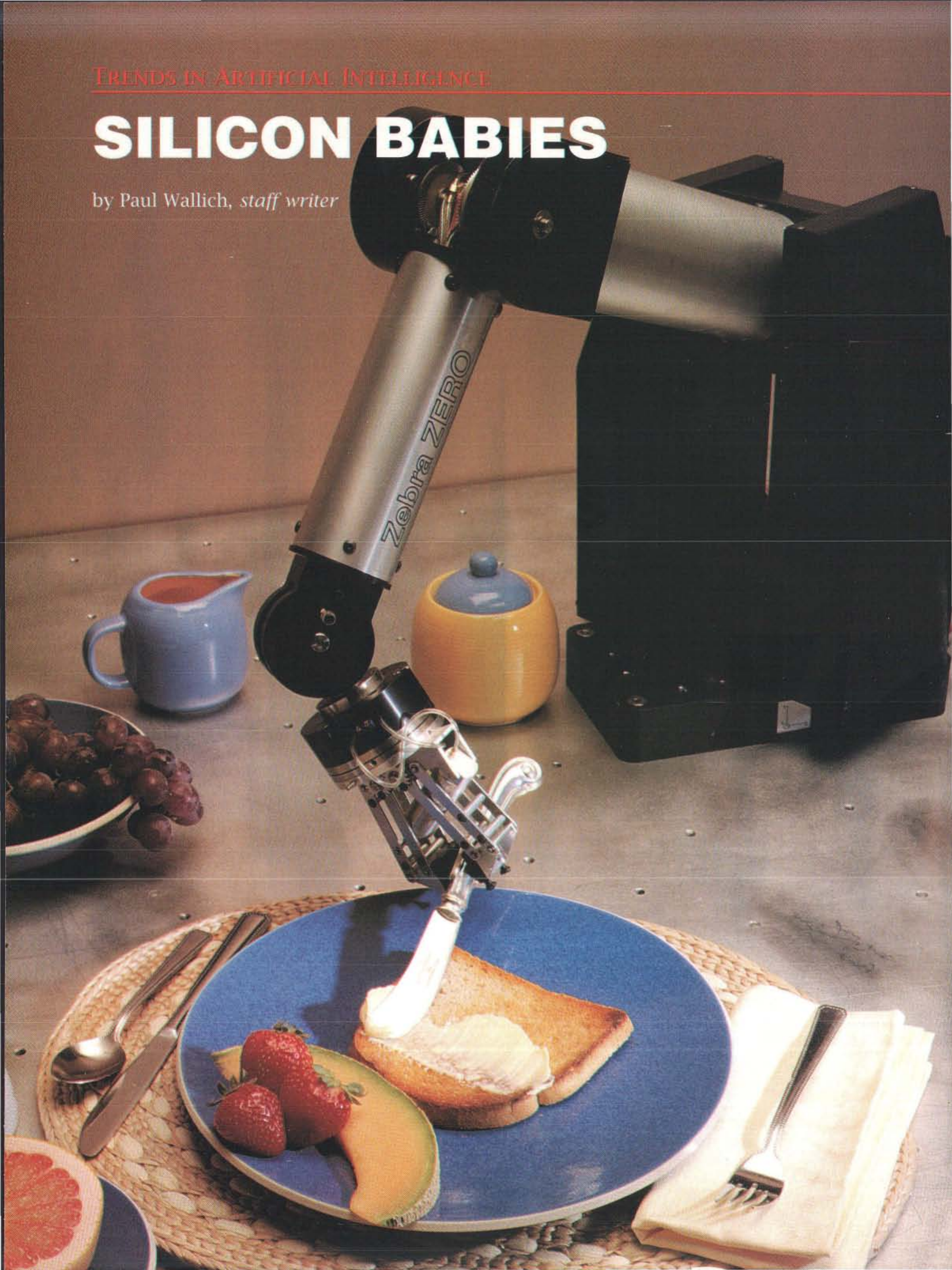
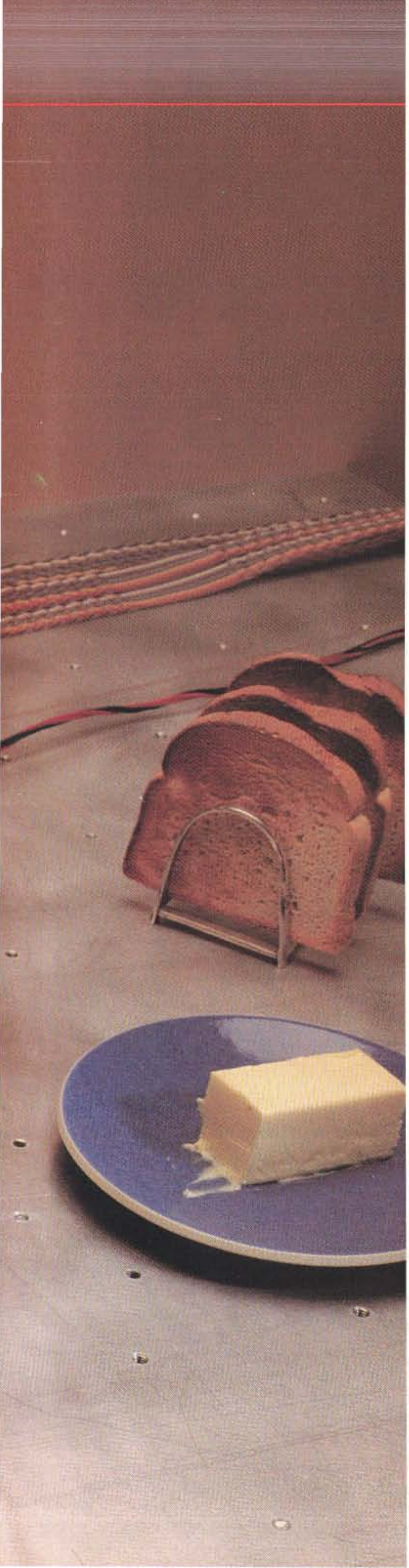
SILICON BABIES

by Paul Wallich, *staff writer*





Researchers are trying to build machines that emulate the reasoning and self-awareness of humans, but in the real world even the competence of a mayfly eludes them—for now.

Squish... Whirr... Scrape. Scrape. Scrape. A robot is buttering toast. It's doing a fairly good job, considering that it is just learning.

Although humans do it easily, by machine standards the simple act of buttering toast is very difficult indeed. It is also a task that stands proxy for a host of other problems that confront machines aspiring to get along in the real world. A conventional robot, which knows only how to move its gripper along a specific path, would almost certainly make a mess of both toast and butter.

Buttering toast requires continuous modification of actions based on sensory feedback. Too much resistance, ease off the pressure; too little, change the angle of the knife, and so on. Calculating the correct path in advance would call for precise measurement of the viscosity of the butter and of the toast surface, a nonlinear finite-element model of the spreading process as well as several hours of time on a Cray supercomputer.

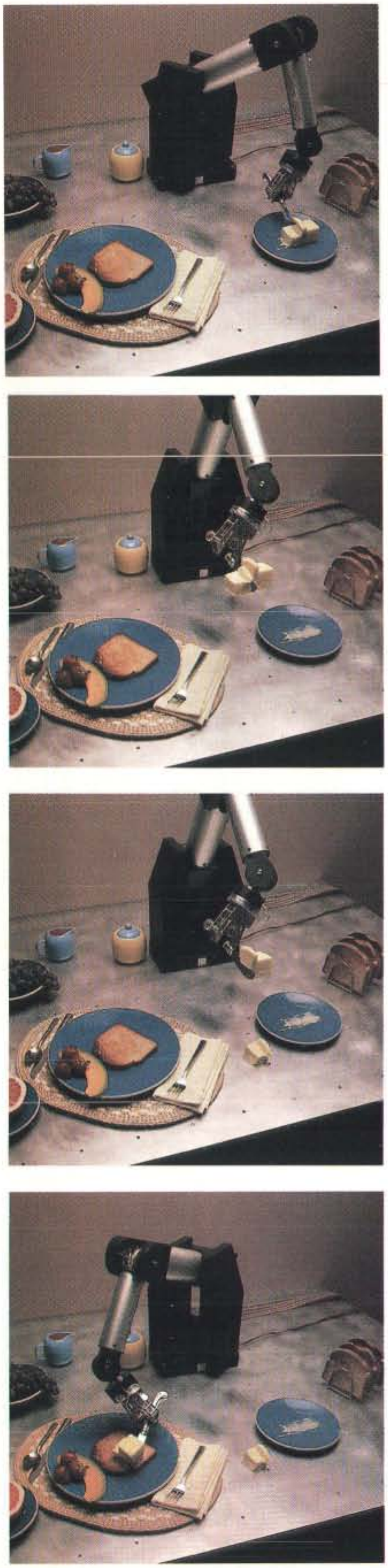
This experimental robot in Stanley J. Rosenschein's laboratory at Teleos Research in Palo Alto, Calif., is one of a new breed of machines that represent the leading edge of artificial-intelligence (AI) research. Unlike AI systems based on vast stores of arcane know-how, such as expert systems, this nascent tribe is supposed to act with perception and be imbued with common sense. The effort is pushing the state of the art not only of machine vision and sensing but also of automated reasoning, planning, knowledge representation and natural-language understanding.

These are the subdisciplines that artificial intelligence split into a generation ago, when it became clear that it would take more than simple programming to produce a computer that could be regarded as intelligent. Then, two years ago, AI pioneer Allen Newell of Carnegie Mellon University issued a call for researchers to put the field back together again, to build what he called "integrated intelligent systems." The prowess demonstrated by AI's parts, he said, was now sufficient to build a whole.

In response, Newell says, "a whole bunch of interesting characters emerged from the woodwork." Most of them were already working on "autonomous vehicles" or "intelligent agents" or just strange things. They shared the common goal

FORCE-SENSING ROBOT can spread butter, but it still can't taste breakfast. Interaction with the world is largely an unsolved problem for machines that aspire to humanlike intelligence and even a sense of their own existence.

How Not to Butter Toast



of attempting to build not just "smart" computers but mechanical creatures that could function independently in the world.

Two major issues daunt those who have responded to Newell's call. Researchers disagree on the fundamental issue of what constitutes intelligent behavior. Second, they divide into at least two major camps on the question of how to get from the current state of the art to whatever they think intelligence may be. Traditional AI researchers such as Newell believe in reasoning, learning and symbolic processing. More sophisticated algorithms and faster hardware, they predict confidently, will eventually engender smart machines. Meanwhile young turks such as Rodney A. Brooks of the Massachusetts Institute of Technology avoid at all costs anything that might look like rationality by designing mechanical creatures that act entirely according to reflex.

Even if a consensus existed among AI researchers (a suggestion that people in the field regard as humorous), putting artificial intelligence back together would not be easy. Expert systems are solving a myriad of problems, from diagnosing the ills of diesel engines to rating midsize banks. Automated planners schedule aircraft maintenance and help design assembly lines. Natural-language systems can parse most sentences as well as a person can. But experience demonstrates that modules from these diverse disciplines cannot simply be combined and work smoothly together.

At one recent workshop, reports Kenneth D. Forbus of Northwestern University, "thing" builders spoke optimistically of an autonomous machine that could perform a variety of tasks and survive unaided in the world for a year. "So I went around and asked people, 'How long does your system last?'"

The answer was that no one had yet built anything that survived more than a few hours. The causes of death are as varied as the machines themselves. Sometimes the software just grinds to a halt, Forbus says, or sometimes the batteries run out. Most often, though, an autonomous system simply gets into a situation from which either reasoning or servomotors cannot extricate it—say, stuck under a chair.

In blunt terms, the integrated-intelligent-systems researchers have yet to build a machine with the survival abilities of a mayfly—much less the sensory and behavioral smarts to find another mayfly and mate with it.

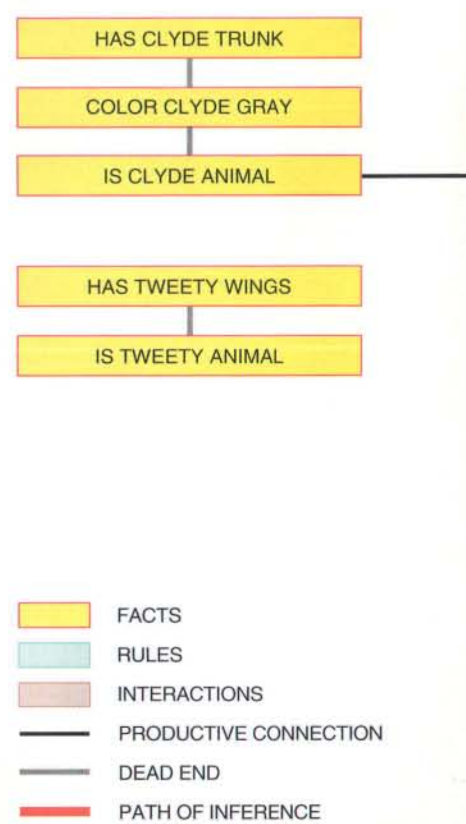
Modules from different parts of AI do not work together, because the re-

Knowledge Representation

Artificial-intelligence programs usually represent their knowledge in the form of logical assertions in a specialized computer language. Some assertions are simple facts—(HAS TWEETY WINGS) (ISA TWEETY BIRD)— whereas others, typically called rules, encode information about connections: (IMPLIES (HUNGRY CLYDE) (GOAL CLYDE (AND (POSSESS CLYDE ?X) (EDIBLE ?X)) (CONSUME CLYDE ?X))) [Rough translation: "If Clyde is hungry, he will want to possess something that is edible and consume it."]

An "inference engine" responds to new assertions by searching its knowledge base for additional facts based on rules and existing facts. For example, if a system were told that Clyde is in fact hungry, it would assert that he has the appropriate goals. That conclusion drawn, the system might search its knowledge base for edible objects and then assert that Clyde wanted to possess and eat one of them (*below*).

Reasoning from knowledge and

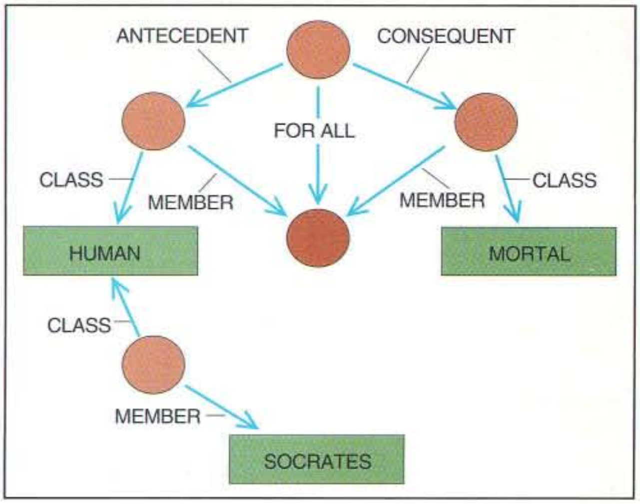


rules to new knowledge is typically called forward chaining. Inference systems can also chain backward from existing knowledge to answer queries. For example, if asked whether Clyde wanted to possess a crescent wrench, the system would see that being hungry can be a reason for wanting to possess an object, and so it would check whether Clyde is hungry and whether crescent wrenches are edible. Failing either of those possibilities, it would continue searching for other rules that might eventually imply (GOAL CLYDE (POSSESS CLYDE CRESCENT-WRENCH)).

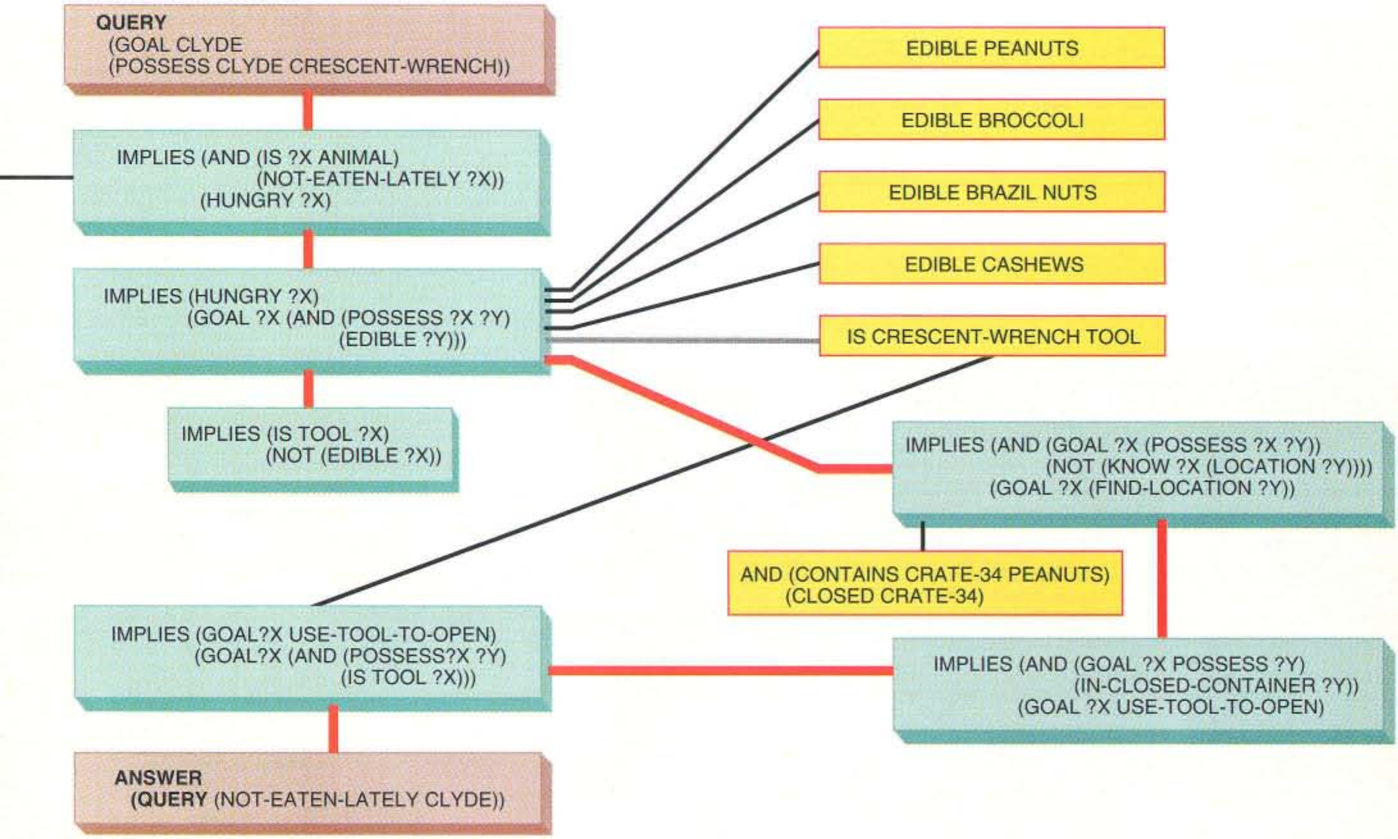
Encoding facts and actions is a tricky problem. Consider the "Gravity drowned" problem: When a natural-language understanding researcher was first trying to represent the concept of falling, he translated "X fell" as "Gravity carried X downward." Elsewhere in his system was a rule that if you fell in a river and could not swim, and had no friends to rescue you, you drowned. Since gravity as a force of nature has neither arms, legs nor friends, it meets its unfortunate—and improbable—end.

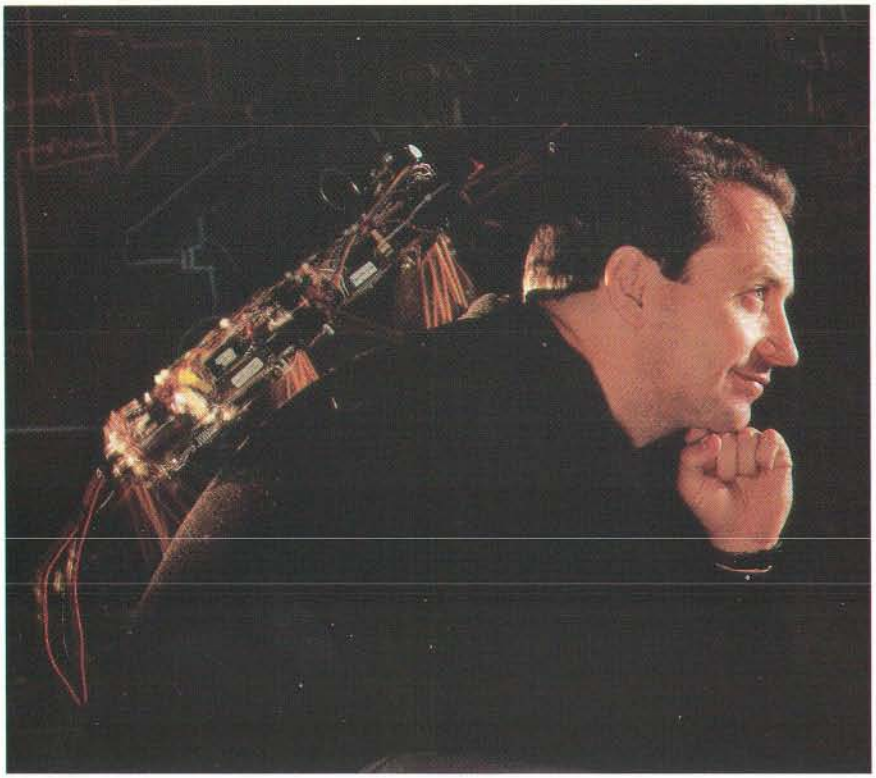
Other facts, such as "Fish swim," are not really facts at all, so attempting to encode them yields endless trouble. Some fish walk on their fins, and others are baked. Researchers have turned to "default reasoning" ("Fish usually swim") and "nonmonotonic inference" (retracting any conclusions that may have depended on the belief that a particular fish swims) to produce automated deductions in the presence of uncertainty and error. The success of both techniques is mixed.

If the objects in a knowledge base have complex relations to one another— and they usually do—researchers often resort to semantic network representations (*above right*). Nets consist of nodes that stand for the object in question and of links that show nodal connections. Links can denote simple relations such as IS-A or PART-OF or more complex ones such as LEGALLY-ENTITLED-TO, BELIEVES or OPERATES-ON. A program seeking to deduce information about a particular object in the semantic network need only follow the appropriate links.



Semantic nets can also use a technique called spreading activation to model human cognitive behaviors such as free association. Spreading activation passes markers outward from nodes representing particular objects or concepts. When the markers from different nodes cross, the paths back to the parent nodes represent a chain of associations between the two objects.





RODNEY A. BROOKS of M.I.T. and thoughtless friend Genghis are leading exponents of the belief that intelligent behavior has no need of reason.

searchers who built them have answered questions that those in other specialties were not asking, and they have for the most part neglected other issues that are turning out to be crucial for integrated intelligence. For example, says Thomas M. Mitchell of Carnegie Mellon, the underlying paradigm of most machine vision algorithms is simply misguided: "Much of the work was how to get a program to interpret a [single] picture" and identify the objects in it. But artificial creatures that exist in the world must interpret a stream of images, each differing only slightly from the one before it. Furthermore, they may care less about the identity of an object than whether they should avoid running into it.

Although machine vision systems are being used in commercial robots, until recently specialists in the field largely ignored the question of vision for mobile machines. Mitchell, for one, believes problems ranging from binocular vision to the identification of ambiguously shaped objects can be solved simply by moving a robot's eyes, not by increasing computing power. He cites work by Dana H. Ballard of the University of Rochester on "animate vision," which has shown that many image-processing algorithms can be simplified immensely by taking into account the fact that creatures can move their heads and can fix both eyes on the object of their attention.

Then there is the problem posed by so-called systems of truth maintenance and default reasoning, which attempt to cope with uncertain or contradictory information. Take, for example, the statement "Birds fly." That's true, as Marvin L. Minsky of M.I.T., among others, has observed, unless they are penguins or ostriches or moas or dodoes, or unless they have had their wings clipped or are confined to a small box, or unless they are dead and nailed to a perch, or unless they have been psychologically conditioned from fledglinghood to stay on the ground, and so on. Instead of cogitating furiously in an attempt to determine whether it should believe a priori that a particular bird flies, Mitchell says, "a robot can just look at Tweety to decide if it can fly."

Attila the Bug

Brooks is the most visible member of the AI faction that wants to consign machine vision, truth maintenance and most of the rest of artificial intelligence to the dustbin of history. They contend that AI's separate subdisciplines have essentially been looking under the lamppost—choosing entire areas of study for their conceptual elegance or tractability rather than for their usefulness. In papers titled "Intelligence without Reason" or "Elephants Don't Play Chess," he argues that the fancy logic and knowledge-representation techniques beloved of artificial intelligencers have no place in machines designed to live in the world.

Instead Brooks pins his hopes on what he calls "subsumption architecture," in which complex behaviors such as exploration of the environment are built up from simple ones like moving a single leg. Subsumption architecture relies largely on the nature of the outside world rather than sophisticated reasoning to structure the robot's actions. For example, if the robot encounters an obstacle, the important thing is to go around it, not to determine how it got there. The robot may not even need to remember that the obstacle is there—after all, it will detect the obstacle perfectly well the next time it approaches it.

Such a procedural knowledge representation, says M.I.T. researcher Pattie Maes, avoids the conventional AI impasse of trying to construct and maintain a consistent logical model of the outside world. "Making the correspondence between perception and internal representations is too hard," she says.

Brooks's insectoid robots, dubbed Attila and Hannibal, contain multiple microprocessors and work by coupling sensors, processors and actuators in a tight loop [see "Mathematical Recreations," SCIENTIFIC AMERICAN, July]. The legs, for example, spend most of their time running a program that checks their position and keeps them standing. If conditions trigger the robot's walking behavior, a central processor sends "Walk" signals to the legs but does not actually coordinate their behavior. The individual programs built into each leg operate independently. Maes contends that the "emergent behavior" of these parallel processes may be a better mimic for what actually happens in the brain than the "folk psychology" of a centralized, all-controlling conscious mind.

As simple as it seems, subsumption can generate fairly complex activity. One of the robots that the group designed wandered the halls of the M.I.T. Artificial Intelligence Laboratory scavenging soda cans (at least once, the published claim goes) without any explicit concept of what it was doing. The "approach" module brought the robot's gripper close to anything can-shaped, and the gripper simply closed whenever anything appeared between its claws.

Brooks has suggested that tiny mobile robots, weighing no more than a kilogram might perform such tasks as

exploring the terrain of a distant planet (or this one) more efficiently than larger, individually more reliable systems.

Working along these lines, M.I.T. graduate student Maja Mataric designed a software module that produces a subsumption-style map of a robot's surroundings. Instead of the usual data structure containing objects and their locations, or perhaps even a robot-sensor view of the world, the subsumption map is a collection of little computational processes, one of which is activated for each "interesting" place in the robot's world.

Maes has even designed a subsumption-based architecture that incorporates "beliefs" and "motivations." A robot based on her designs would be potentially able to answer the question "Why did Attila cross the road?" The robot could tell a human being where it thought a particular object was located or what caused it to go from one room to another. Much like the "behavior" agents that drive walking or scavenging behavior, the "belief" agents in Maes's so-called agent network architecture govern the robot's actions at a high level. For example, a "battery low" belief agent might suppress exploration in favor of a "return to base" behavior.

Predictably, the makers of more conventional, less photogenic systems are charitable toward Brooks at best, hostile at worst. Nils J. Nilsson of Stanford University, who directed AI work at SRI International 20 years ago in the days of Shakey, the first mobile robot, retreats to W. H. Auden when pressed for an opinion: "Those who will not reason/Perish in the act: /Those who will not act/Perish for that reason."

Mitchell is blunter. Brooks and his colleagues, he says, "are very seductive, but they have very bad ideas." Although he admits that Brooks's team has been "surprisingly successful in building systems that behave well," Mitchell contends that the subsumption architecture is better suited to building thermostats than intelligent agents.

Yet one of the most approving comments comes from Newell, whose SOAR architecture is the apotheosis of elegant reasoning and knowledge representation. Newell contends that SOAR and subsumption are not really so very different, because SOAR, too, operates essentially on a stimulus-response basis except when its rules run into an impasse. He praises the idea of "reactivity" that he sees in the little insectoids.

Regardless of whether Attila and its kin scuttle to fame or blunder into a philosophical dead end, or do both, Brooks's work raises some fundamental issues about the nature of intelligence. What does it mean to say that a system knows something? Is it enough for the system to behave as if it knows not to run into walls, or must it have some explicit representation of structural engineering?

Researchers may find it simpler to think in terms of logical propositions and inference, Rosenschein says, but that does not mean everything inside a machine must be represented in terms of explicit logic. "Some people are impressed by the precision of logical languages and their capacity for rubbing facts up against one another," he says, but in real machines elegance must defer to efficiency. Determining the truth of a logical proposition is an "NP-hard" problem, one that in principle cannot be solved in any reasonable time. That is not a good thing for a mobile robot to be computing.

The problem, Rosenschein contends, is that designers in pursuit of logical elegance mix static facts, which are always true, with dynamic information about the immediate state of the world. Facts that can change, such as who works in what office or whether the elevator door is open, benefit from explicit representation. But constants such as gravity or the impenetrability of material objects need not be explicitly coded. A system has only to act as if it knows them. Rosenschein and his colleagues have developed software tools that build the static knowledge into the structure of an autonomous system.

But the designer of an intelligent machine must still decide what knowledge the system should appear to have and how that knowledge should appear to be represented. The issues are far from resolved. Standard logic, for example, can represent facts, but it cannot represent intentions or beliefs about the world or about the results of particular actions, says Stuart C. Shapiro of the State University of New York at Buffalo. Richer logical formalisms bring with them the danger of creating paradoxes that can bring a reasoning engine to its knees, he notes [*see box below*].

Furthermore, Shapiro says, the logic of belief and the logic of action are not the same. Software based on conven-

The Paradox Explosion

The barber shaves every man who does not shave himself. Who shaves the barber? With these simple sentences Bertrand Russell demolished the apparent perfection of predicate logic and mathematical set theory. The barber paradox (or, for the set-theoretically inclined, the set of all sets that do not contain themselves as members) illustrates the pitfalls of allowing statements to refer to the truth of other statements.

Artificial-intelligence researchers care about this ancient chestnut because most of their programs are firmly based on logical inference. The laws of logic provide that it is possible to deduce anything from a contradiction, and so the possibility of paradoxes spells disaster for AI.

The incantation runs as follows: if "A" is true, then obviously "A or B" is true. Meanwhile, if "A" is false and "A or B" is true, then "B" must be true. But a contradiction says that "A" is true and "A" is false, and so "B" must be true whatever it is.

There are two paths out of the quandary, according to Stuart C. Shapiro of the State University of New York at Buffalo. One is the version that mathematics chose: first-order predicate logic, which does not permit statements that refer to one another's truth value. No paradoxes, but the system is incomplete, as Kurt Gödel showed in the generation after Russell. A statement may be manifestly true but impossible to prove in formal terms.

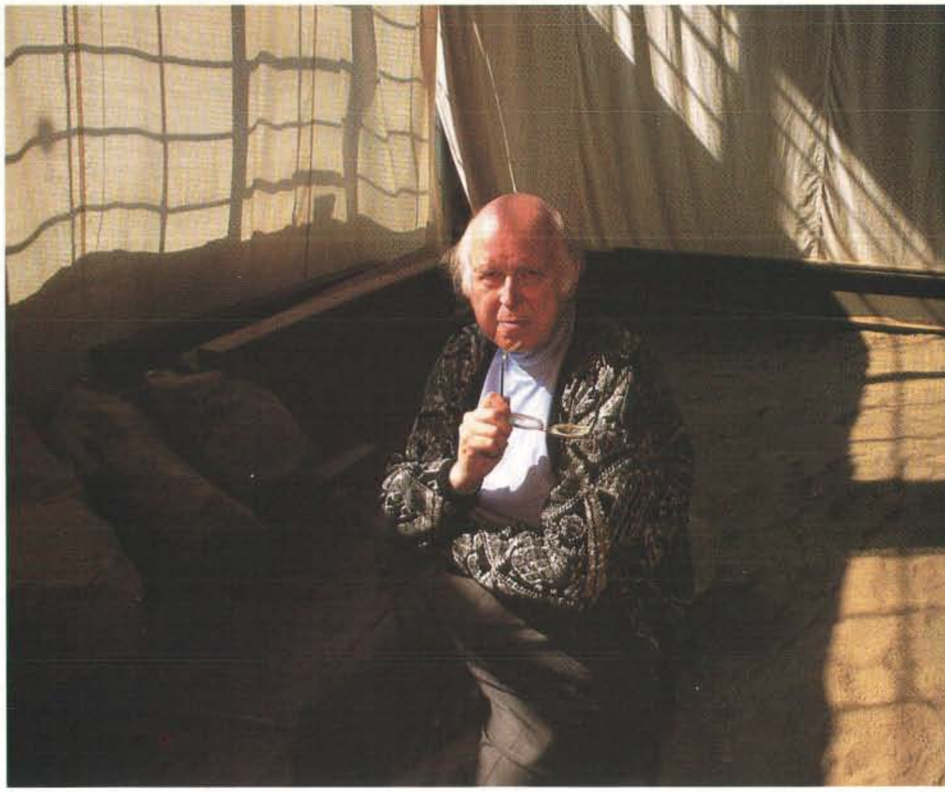
The other path is to impose (logically speaking) arbitrary constraints on relevance, so that deductions cannot simply run away into infinity, Shapiro says. Knowing that the moon both is and is not made of green cheese, for example, might lead an automated reasoner to bizarre conclusions about lunar soil samples, but it should not permit the machine to decide that the color of the sky determines shipping tariffs for Tibetan yak fat.

Ironically, Shapiro explains, the structure of simple automated deduction systems prevents such blowups automatically. These programs never try to reason from items that are not directly linked to one another. Only the most sophisticated and complete programs, after long and arduous work by their authors, can haul together completely unrelated facts and explode when confronted by a contradiction.

tional logic, such as the PROLOG programming language, typically forms a belief only once, even if it is used as a logical step in several different chains of reasoning. Applying the same economy measure to actions would lead you to conclude, for example, that you had no need to walk in order to get out your front door in the morning, because you had already walked when you went to the bathroom to brush your teeth.

Logical representations capable of dealing with both actions and beliefs are essential to intelligent agents. Not only will such machines be required to reason about the consequences of their own actions, Shapiro points out, they also will have to represent and understand the beliefs and actions of people and other intelligent agents. For example: "John believes that Mary believes that the program is faulty, but John believes that the program is not faulty, and yet Mary is right."

Such logical regressions are reflected in the work of Thomas Dean of Brown University, among others. Dean's systems not only plan out their actions, they even plan how much planning to do. Those who think about these "anytime algorithms" are painfully aware that computing resources are not infinite—like people, machines can exercise only what Herbert A. Simon calls "bounded rationality."



PROBLEM SOLVERS Allen Newell of Carnegie Mellon University (*left*) and John E. Laird of the University of Michigan are two chief architects of SOAR, an integrated reasoning system that is now nearing its 10th birthday. Variants of the system can

Chunks of Knowledge

Reasoning techniques that produce exact answers eventually are no good to machines that must operate in "real time." (The precise definition of real time is also a matter of controversy, but Mitchell offers the handy rule of thumb that the time spent thinking generally should not be longer than the action being thought about.) Indeed, reasoning techniques that quickly produce approximate answers may not be any good either if they cannot be interrupted partway through. As anyone knows who has watched a treasured possession heading for the floor, virtually any action may be better than inaction.

Advocates of such meta-planning tend to use algorithms based on "iterative refinement." Run them once and they produce an answer, again and they produce a better answer, and so on. Given information about how answers improve with time and about the cost of delay, a system can decide how long it should think before acting. There is, Dean admits, yet another level of regression: optimizing the amount of time to spend planning is itself an unsolvable problem, so the meta-planner must either make approximations or else plan how much time to spend planning how much time to spend planning...ad infinitum.

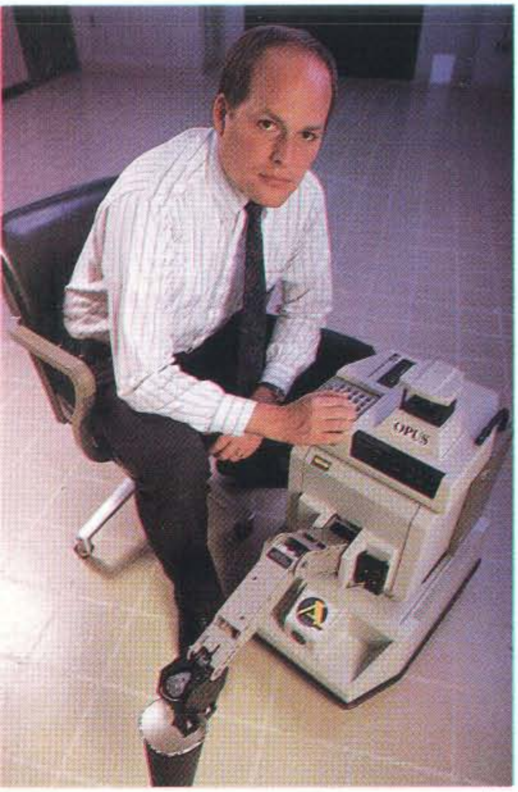
Dean has proved mathematically that the logical regression "eventually bottoms out," but he acknowledges that intelligent machines based on his algorithms are still in their formative years, "just at the stage where they're robust enough to walk down the hall without leaving huge gouges in the plaster." He predicts that it will probably be the end of the decade before most planning and reactive systems stop using what amounts to ad hoc methods to allocate computational resources.

One such relatively simple logic scheme is the brains of SOAR, a logic system that Newell's group has been running in various incarnations for nearly nine years. It is based on two techniques: search and "chunking."

When the system is confronted with a problem, it checks whether any of the rules in its knowledge base apply and fires off a train of deductions until it can go no further. If the problem is solved, fine. If not, SOAR (which once upon a time stood for State, Operator And Result) sets up a "problem space" to deal with the impasse. Within this problem space, it searches for all possible solutions, using special-purpose techniques if they are available and brute force if not. Once SOAR has found an answer, it generalizes the technique it used in the solution and compiles the technique into a "chunk"—a rule that will be activated the next time a similar question comes up and so eliminate the burden of searching.

SOAR's module for natural-language understanding (NL-SOAR) is a perfect example of this technique, Newell says. It simply applies the operator "Understand this word in context" to each new word of input, rattling off deductions, and chunking with abandon. According to John E. Laird of the University of Michigan, who developed SOAR along with Newell and others, NL-SOAR starts with about 900 rules and expands its knowledge base to more than 1,500 after comprehending only a few hundred words. Newell claims that the system is, in principle, capable of learning new words and rules indefinitely. He speaks of running SOAR for a month straight, continually "adding knowledge in interesting ways."

Then he backpedals. As the system stands now, "that's not to say that it won't seize up in a couple of hours," he says. The flaw resides somewhere in the initial rules that humans have hand-coded into the system. Somehow



control mobile robots, understand plain English and perform a variety of other more or less practical tasks.

the structure of these chunks makes for bad learning. Oddly enough, Newell says, the fewer rules people put in and the more SOAR has to learn by itself, the better it works.

In addition to the natural-language system, SOAR also runs a couple of robotic applications: RoboSOAR, a robot arm, and HeroSOAR, a mobile robot. RoboSOAR, which depends on a separate vision module to determine where small objects reside in its work space, can perform simple tasks such as picking up and stacking blocks. HeroSOAR investigates its environment with ultrasonic sensors, paying special attention to things that look like garbage cans.

Ultimately, Laird says, all the different modules of SOAR will be incorporated into one. That will enable a robot to accept plain English commands and answer back in kind as it performs its tasks. But first the researchers have to solve some problems with the vision system and other modules.

The vision software analyzes scenes in a form that does not always match the information that SOAR's problem solver might want. Furthermore, the camera is mounted directly above the robot's work space so that RoboSOAR can't actually see what it is doing. The system must analyze a scene, move its gripper and attempt to pick up objects, then move the gripper out of the way and find out whether it has been successful. It's a little bit like a human being wearing heavy mittens trying to play chess by taking a snapshot of the board, deciding what move to make and then, eyes closed, reaching out for the piece.

Like SOAR, Mitchell's THEO system uses a conceptually similar "plan then compile" architecture. Mitchell contends that integration is not nearly enough; organization is the key. Without some way of focusing on the facts relevant to the case at hand, a program will bog down. "We quickly learned that if a system has five rules it does okay, but 5,000 rules will slow it down hopelessly," he says. (Newell reports the same experience with SOAR. Adding a single "expensive chunk" to the knowledge base can set off a logical chain reaction that reduces the program's speed by a factor of four.)

Besides cluttering up memory space, much of what a system learns by looking at examples, though true, may be irrelevant or even misleading. Mitchell likens the problem to an automated version of the "cargo cults" that led Pacific Islanders to build airstrips and wooden aircraft to entice Western goods and know-how from the sky.

Chunking, Mitchell explains, may speed up the execution of plans, but it doesn't make them any more correct. If the plan is based on an erroneous understanding of the world, it will sometimes fail. Ideally, an intelligent system would learn from its failures, but getting it to learn the right things is a problem. "There is no perfect model for the effects of some actions," Mitchell says, so the best course may in fact be to let THEO fail every now and then and try to recover from its failures, rather than try to anticipate beforehand everything that could go wrong.

AI Meets Virtual Reality

One requirement that Mitchell emphasizes when he talks of letting THEO and other intelligent agents "experiment" with the world around them is that no harm must come to the robot or its subjects. So a number of intelligent-agent researchers have created computer simulations to exercise the programs that will be the brains of their autonomous machines.

One of the simulacrum dwellers that other researchers find most impressive is Homer. Built by Steven A. Vere of the Lockheed Artificial Intelligence Center in Palo Alto, Calif., Homer is a virtual submarine that lives in an aquatic world containing ships, fish, whales, other submarines, mines, buoys, birds, islands, docks and people.

Homer understands about 800 words and can carry out multistep tasks—for example, "Bring the red buoy to the dock before noon and then meet Roger at the breakwater tomorrow morning." It knows how to ask people for information when it doesn't know where something is, and it continually tracks events in its environment.

In fact, a printout of a session with Homer bears a strong resemblance to a transcript of a day spent with a precocious three-year-old:

"I see a brown bird on the gray log."

"There are two sailboats by the island."

"The *Smirnov* just passed me on the right again."

"I have reached the dry dock."

"Homer, bring me Fred's buoy."

"Now I'm going to Fred."

"Fred, where is your buoy?"

Vere admits that having a simulated world to work in has simplified much of his work, but he insists that most of Homer's capabilities could be transferred to a real minisub. In particular, he says, Homer's uncannily acute simulated vision is not particularly farfetched. Because the marine environment contains a set of objects so small, a fairly simple perception system would be able to distinguish between fish, whale, ship, sailboat, log, bird and landmass. Homer would be even more competent if it were transplanted to a conceptually similar (although geographically disparate) artificial environment such as a space station, where every object could be marked for unambiguous identification.

At first glance, Homer appears to be a success story for integrated intelligent architectures. It can plan its actions, change plans in response to new circumstances and interact with others. Under the surface, though, the sailing is not so smooth, Vere says. Homer is slow, and its memory is inefficient. The longer it lives, the slower it runs. Just a few scenarios strung together will bring the program to a near halt. "It's like a house of cards," Vere laments. "When you add a new capability, you discover that old scenarios don't work any more. You have to go back and retune it."

Homer's life is also threatened by corporate budgetary woes and the gradual extinction of its research team. Vere's colleague Timothy W. Bickmore left Lockheed a year ago, and the company now permits Vere to spend only half of his time on the project. Although new computer hardware has

helped improve Homer's reaction time from miserable to tolerable (30 seconds to plan a simple course of action, down from several minutes), the dream of transplanting it to a real minisub is on indefinite hold.

Just down the road from Vere, at the National Aeronautics and Space Administration Ames Research Center, another simulated agent has a somewhat firmer footing. Mark E. Drummond's Entropy Reduction Engine (ERE) is a conceptual model for the kind of robot that might one day help maintain structures in orbit or on the moon.

For now, ERE lives in Tile World, a gridded Flatland that contains any number of polygonal tiles. Tile World is beset by winds that can move tiles from their places, and the robot's attempts to move or clutch them in one or more of its four grippers may fail. Such a simple environment provides more than enough diversity to work out most of the important issues in planning and control, Drummond says.

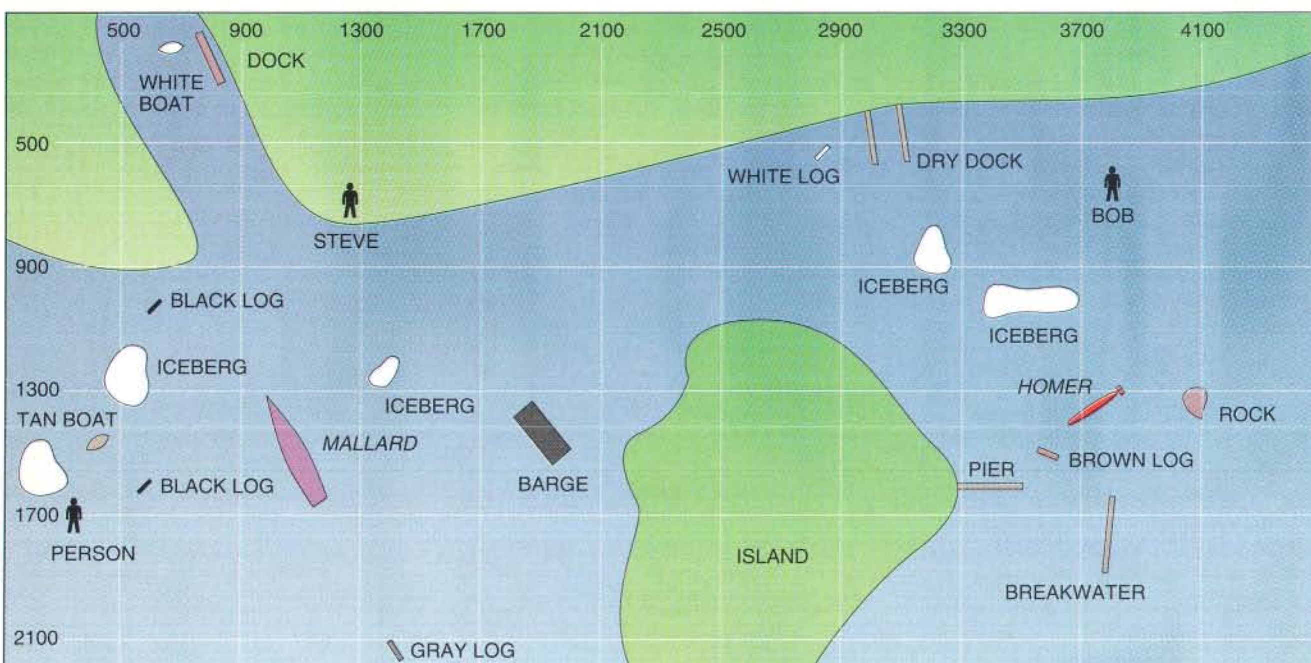
ERE consists of components that decompose problems into simpler form, evaluate possible solutions and compile rules that put those solutions into effect. It is designed not only for "achievement goals," such as assembling tiles into a particular configuration, but also for what Drummond calls behavioral constraints—for example, making sure that a particular tile structure remains intact even under the influence of winds. (Eventually, of course, Drummond would like to be able to generalize such behavioral constraints to build the kind of robot that could be told: "Keep the space station in working order. This is a list of what can go wrong. Here are your tools and supplies.")

Drummond's interest in Tile World, however, goes beyond his own research. He hopes to promote the simple simulated environment as a standard within which the designers of different intelligent agents can compare their performance on various standardized tasks and thereby understand the strengths and weaknesses of various architectures. NASA Ames, along with Rosenschein's Teleos, has won a research contract from the Defense Advanced Research Projects Agency to define a set of benchmarks for integrated intelligent systems.

At one end of the spectrum of intelligence and action scuttle Brooks's insectoid robots. In the middle are the dozens of systems, such as those built by Vere and Drummond, possessing varying levels of knowledge and capability. At the other end majestically sits Douglas B. Lenat's Cyc, which knows almost everything—1.43 million interconnected facts at last count—but does almost nothing at all. Indeed, many would question Cyc's inclusion in a list of integrated intelligent systems because it is essentially an automated encyclopedia (hence the name).

One problem with conceiving of Cyc as an entity (even though, like SOAR, it is nearing the end of its first decade on this earth) is that Cyc has no real sense of itself, says Patrick Hayes of Stanford. Hayes, currently president of the American Association for Artificial Intelligence, was briefly head of Cyc's West Coast office until conceptual differences with Lenat made him decide to be a consultant to the project instead. "Cyc knows that there is this thing called Cyc and that Cyc is a computer program," Hayes says, "but it has no idea that *it* is Cyc."

Even so, the program is remarkable. MCC, the consortium of 56 high-technology computer companies that em-



SIMULATED SEA WORLD is the domain of Homer, an intelligent agent built by Steven Vere of the Lockheed Artificial Intelligence Center. Homer understands simple English commands and can make plans to carry them out.

ploys Lenat, has invested half a programmer-millennium of effort into Cyc. There is probably an equal amount of work again remaining before—sometime in 1994 or 1995 by Lenat's hopeful reckoning—Cyc reaches the break-even level of about 10 million facts. At that point, it will be able to pick up new knowledge more readily by reading than by having knowledge engineers spoon-feed it. A wider information base may also save Cyc from such gaffes as concluding (from everybody it knew about) that all humans in the world are friends of Doug Lenat.

WUNDERKIND Douglas B. Lenat of MCC is the instigator of Cyc, a decade-long project for encoding common sense. At its birth seven years ago, Cyc was considered near lunatic by many artificial intelligencers; now it is part of the mainstream.

No Royal Road

The program is designed to have the kind of knowledge that an intelligent agent might need to perform its tasks: what people and trees and omnibuses are and how they interact, how objects fall and break, or how a light bulb works. Lenat envisions a day when Cyc will field requests for commonsense knowledge from programs for natural-language understanding, from expert systems in search of sensible behavior near the edges of their expertise. Cyc might even help people decide what kind of automobile to purchase. Almost anything might be relevant, he notes, from changing gender roles in the modern family to the relative traffic citation rates of cars painted navy blue or arrest-me red.

For all its size, Lenat says, Cyc is "kitchen-sink engineering." Everything it knows is asserted in two different forms: first in clean and elegant "epistemological language" and again at the heuristic level in "a grab bag of different representations" that are designed to make inference faster for a particular class of facts. Thus far the system contains 27 different special-purpose inference engines, and Lenat intends to add more as they are needed.

Cyc thus avoids the trade-off between expressiveness and efficiency, Lenat contends. For example, by employing "a tool kit of partial solutions," Cyc has solved the problems of dealing with time, space, causality, belief and intention that frustrate other artificial intelligences. "Most of the power—positive or negative—of integrated intelligent architectures will come from the content, not the architecture," Lenat asserts.

Moreover, Lenat believes the idea that one particular structure of algorithms will make intelligent behavior possible is wishful thinking. "Intelligence is 10 million rules. If you have a halfway decent knowledge representation and a quarter-way decent architecture, they won't get in the way," he says. Researchers who think that a single elegant theory can solve all the problems of knowledge representation and inference suffer from "physics envy," Lenat contends. "They want a theory that's small, elegant, powerful and correct, and so they try one free-lunch tactic after another."

All the philosophical debates and engineering talent may seem a little much for picking polystyrene cups off the laboratory floor—assuming, that is, the containers are not glued down. When will the life span of integrated intelligent systems break the 24-hour barrier, and how?

It is tempting to believe that the natural progress of semiconductor wizardry will let people solve problems of perception and reasoning by brute force. After all, as Newell says, "if not for the fact that workstations have doubled in power every year, we'd be dead already." Faster, cheaper chips have already put mobile, camera-bearing robots within reach of most research groups.

In reality, however, Newell admits that integrated-circuit advances have at best kept big projects like SOAR a few paces ahead of the knackers. He is not happy thinking about the performance of systems containing perhaps 200,000 rules instead of the paltry few thousand that his machines run today. Mitchell concurs: "We'd like to think that silicon will save us, but it won't."

The answer instead may be nothing more complex than time and hard work. By their very nature, Newell points out, integrated intelligent systems are jacks of all trades—not on the forefront of any particular field of artificial intelligence. And now that planning, natural-language understanding and other disciplines have matured, he says, "you have to walk a long way to get to the frontier." But if artificial intelligencers can muster the determination to continue long beyond the span of any single graduate student or research grant, their silicon babies may yet grow to inhabit working bodies.

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Rethinking Research

Bell Labs seeks a new model for industrial research

"The man who embraces a new paradigm at an early stage must... have faith that the new paradigm will succeed....

"Something must make at least a few scientists feel that the new proposal is on the right track, and sometimes it is only personal and inarticulate aesthetic considerations that can do that."

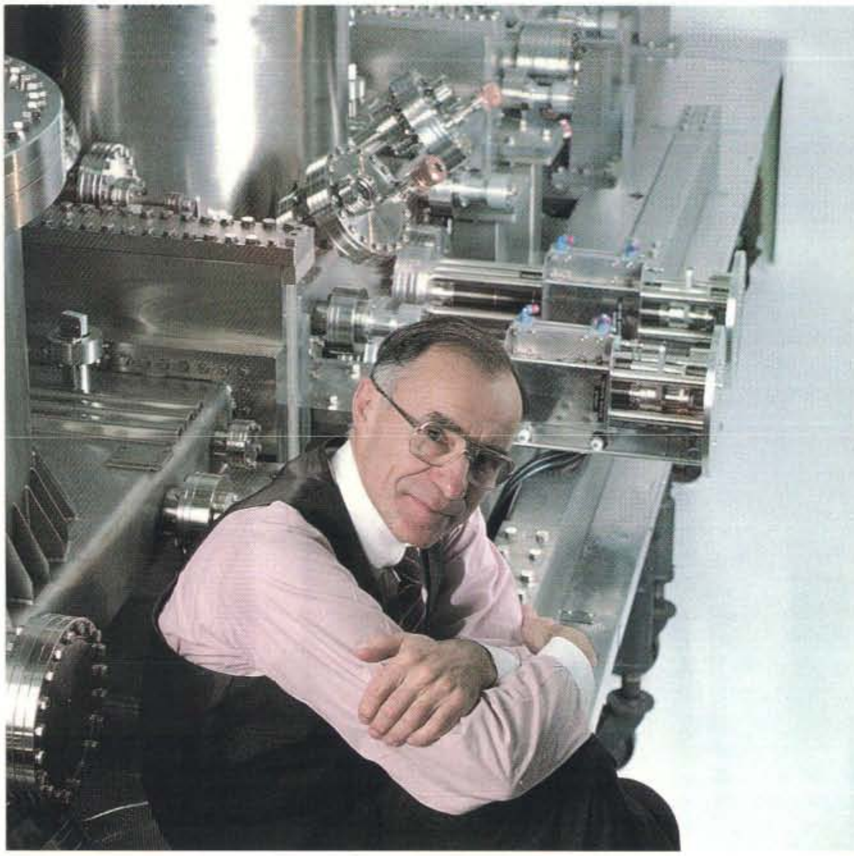
—THOMAS S. KUHN, *The Structure of Scientific Revolutions*

It's a summer evening at AT&T Bell Laboratories in Murray Hill, N.J.; the offices are quiet. Henryk Temkin walks a visitor down a long, concrete corridor, one that dozens of America's greatest scientists have trodden in years past, to a laboratory crammed with equipment. There a metal-organic chemical vapor deposition machine is coating a semiconductor wafer with layers of other semiconductors, each barely a few atoms thick.

Temkin has earned an enviable reputation among the scientific elite for creating exotic structures with such tools. But since November 1990, he has devoted his energies to a more humble albeit more pragmatic goal: improving the process for manufacturing a particular type of solid state laser. Temkin will not publish a paper or give an invited lecture on this work. But in a break with the past, one of AT&T's development groups is already putting his ideas to work on a production line.

Even though the project has not yet run its course, it has already aroused both satisfaction and dismay among Temkin's colleagues for reasons that have nothing to do with the quality of the work. The project is a bellwether of the changes resounding through the heart of Bell Labs—the so-called area 11 research group that gave rise to the transistor, the laser and other Nobel-quality efforts. The very purpose of doing research is changing at Bell Labs.

The task of reorganizing and rethinking the role of research has fallen largely to Arno A. Penzias, vice president of research and a Nobel laureate honored for his co-discovery of the cosmic background radiation. More than a year ago



ARNO A. PENZIAS, vice president of research at Bell Labs, must both preserve the quality of research and make research pay its way. Photo: Louis Psihoyos/Matrix.

Penzias embarked on a sweeping reorganization of the research divisions of Bell Labs. The immediate aim was to reduce duplication of research efforts and to tie scientists like Temkin more closely to AT&T's engineering and development teams, called business units.

More fundamentally, however, the changes have meant that Bell Labs, the epitome of U.S. industrial research, is abandoning the paradigm of research that it had so zealously cultivated over the past few decades. In the post–World War II era, Bell Labs researchers and the more corporate AT&T troops led comfortably separate lives. AT&T took parental pride in the research division, boasting about its scientific prowess in advertisements and annual reports. The research staff, in turn, believed its mission was to push back the frontiers of science—possibly for the benefit of the company but primarily for the advancement of knowledge.

That model, of a pure research laboratory nestled inside a mammoth, profitable company, no longer seems to work. The reasons are as stark as the headlines of any newspaper. U.S. technology companies—from IBM and AT&T to more modest enterprises—are in a state of crisis. Market shares are falling prey to foreign competitors. Costs for everything from capital equipment to health care insurance for workers are ballooning. Products are creeping too slowly from the laboratories into factories. As a result, change at Bell Labs is overdue, Penzias declares. Over the next five years, he says, "the test is not going to be whether we do good science or not. The test is: Is the company going to be healthy or not?"

The hunt for a fresh paradigm, a new way to structure and conduct research, is still in its infancy. As a result, Penzias and other company managers are struggling to answer the questions that defeated dozens of U.S. industrial research groups during the past decade:

What is the purpose of research at a company? Why should a corporation support any basic research outside of its immediate interests? Can research efforts both advance science and bolster the corporation that sponsors them?

"I don't know how to do it perfectly, and I don't know anyone else who knows how to do it perfectly," Penzias candidly observes. "If I did, I would go there and spy on them." Penzias has nonetheless charted a course. Projects such as Temkin's may help improve his navigation and even provide anecdotal evidence that the new model works—or that it does not.

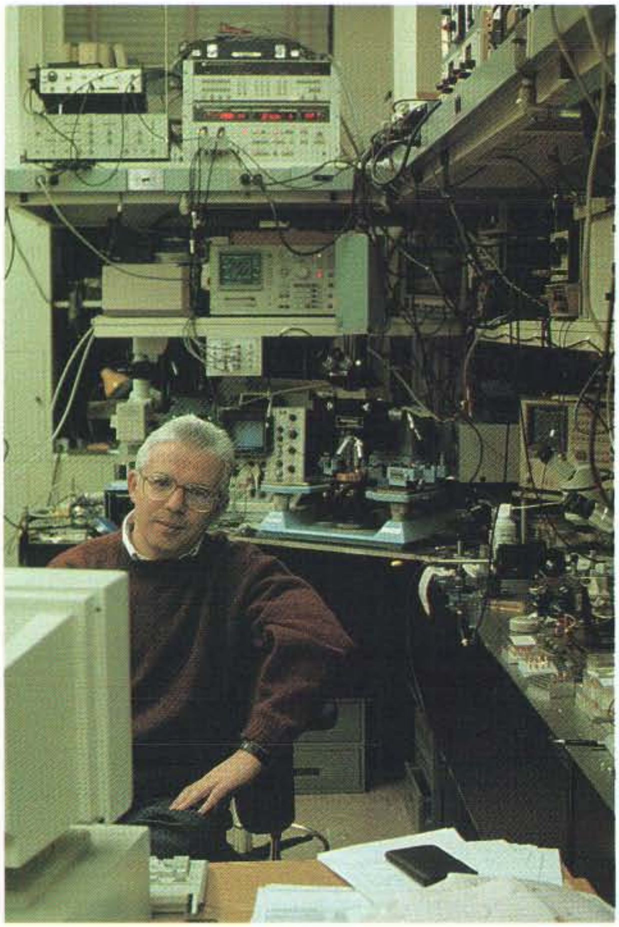
Meanwhile the process of change has been wrenching for many Bell Labs researchers who do not yet have faith in the new directions. Many wonder whether the evolving structure will continue to foster fundamental research, particularly in solid state physics and materials. And where, they ask, if not at Bell Labs, will such research be carried out?

"I feel like an endangered species," laments Alan Huang, a 10-year veteran of Bell Labs and a leader in optical computing. "As a stockholder of AT&T, I can understand why changes are taking place. As a taxpayer of the U.S., I cannot understand why," he says. "It's not just AT&T. America is close to another intellectual dark age, another technological dark age."

"The world," Penzias concurs, "is simply not as comfortable a place as it used to be." Pointing to a nearby tape recorder, he declares: "The big problem is that it wasn't made in Cleveland. The research that went into that device didn't come from the United States. So whose fault is that? You could say part of it was my fault because I've been a research manager and in research for the past 30 years."

For Penzias, the challenge is finding a way to spin research into products faster and yet preserve the environment that led to so many breakthroughs in basic science, including his own Nobel Prize. The structural changes that he has undertaken are straightforward: he slashed duplicate research efforts by consolidating projects into 15 laboratories divided among four divisions. Over the past year he has also begun sliding the balance of funding away from high-cost and relatively low-payoff work, such as basic physics and materials science, toward the more lucrative software and information technologies.

Finally—and most important—Penzias has been nudging almost half of his 1,200-person research staff into supporting business unit projects. AT&T created business units about two years ago by reshuffling its engineering and marketing staff into specific application areas, such as transmission systems and consumer communications services. Penzias, in turn, has assigned each of his 19 directors the task of working with one of the business units.



RESEARCHER HENRYK TEMKIN is now refining a process for manufacturing specialty lasers. Photo: Jason Goltz.

These research directors must then encourage cooperative projects between Bell Labs scientists and business unit teams. "Years ago you'd hire people here, give them an order pad and a lab, and say, 'Do whatever you want,'" Penzias says. "Today we're using that same tradition of freedom in a different way. We're trusting our people in research to form partnerships with development organizations." So far some 100 to 200 such partnerships have sprung up.

Those kinds of relationships mark a radical change from the days when research remained aloof from development. Paul A. Fleury, who directs the physical research laboratory, characterizes the past attitude as the "Field of Dreams" syndrome: the belief that if research invented it, applications would naturally follow. "We felt our job was done when the papers were written and published," Fleury notes. Now research must carry the ideas much further.

Far more difficult than reorganizing the structure, however, has been instilling the new research religion into the soul of Bell Labs—remolding the lab's values, priorities and rewards. Some of the researchers having the toughest time adapting are those who have not found a connection to a business unit. They (and their managers) must sort out which of their research directions legitimately fall into the "knowledge base" that AT&T might one day need—and which do not. For many of these researchers, trying to find the boundaries is like playing blindman's bluff in a mine field.

For instance, for the past six years or so, Huang had relentlessly and energetically pursued a single goal. He aimed to build an all-optical computer, one that ran on light, or photons, rather than on electrons. His approach won him a mixture of admiration and scorn from others in the electro-optics community, many of whom believe that a more sensible strategy would rely on a hybrid of optical and electronic components.

Still, along the way to an all-optical computer, Huang and his team of a half-dozen researchers scored some noteworthy successes. They played a key role in inventing a kind of microlaser ensemble, called surface-emitting lasers [see "Microlasers," by Jack L. Jewell, James P. Harbison and Axel Scherer; SCIENTIFIC AMERICAN, November]. They helped push the use of integrated-circuit technology to craft tiny arrays of optical lenses and built some of the first all-optical logic gates. "So, even though we were directed to optical computing, a handful of people have already produced other things that will be fields unto themselves," Huang declares.

Yet the reorganization cooled Bell Labs' enthusiasm for Huang's work. "Having Alan Huang and his ideas is

just fine," says William F. Brinkman, executive director of the physics division. "But you don't want to grow that to a large effort because the business is very uphill."

Once Huang needed only to push the boundaries of optical computing to win support and kudos within Bell Labs; now it is unclear how his group should be contributing to the company. "The messages are vague," says M. Christina Gabriel, one of Huang's staff. "If what's needed is for the company to start leading us, then we should go in a certain direction. But we're just hearing 'Go ahead—but do with less money.' And maybe you'll get cut off," she says.

Over the next five years the test is: Will AT&T be healthy or not?
—Arno A. Penzias

The ambiguities and stresses of the new environment are evident even in Bell Labs' showcase effort of teaming of research and development, namely, Temkin's effort to develop better manufacturing procedures for specialty lasers. The project began to take shape when the AT&T microelectronics plant in Reading, Pa., needed help in developing techniques for fabricating solid state lasers that could operate in very hot environments.

After much negotiation, Temkin and his colleagues devised a two-part approach. In one room at Bell Labs, using equipment they have worked with for years, Temkin and his colleague Ralph A. Logan whip up batches of miniature laser wafers, testing dozens of combinations of fabrication conditions. Across the hallway is a new machine, this one identical to the equipment used by their Pennsylvania colleagues to build much larger wafer arrays.

Once Temkin and Logan have reached some conclusions based on their experimental equipment, they walk across the hall and try out the ideas on the larger, production machine. Successful procedures are then relayed to the Pennsylvania team.

Ironically, Temkin has found that communicating progress to management in the research division has turned out to be tougher than sharing details with his colleagues in production. "We have a structure in which engineering [as opposed to science] is not understood, and yet it is supposed to be the most important part of my job!" he says. One manager asked him: "'Are you still doing this grungy stuff?'" At least, Temkin says, "he recognized that there is a period of grungy stuff that has to be done."

Temkin also wonders how he and his colleagues in research will be rewarded for their efforts. In the research divisions, he points out, there is little tradition of celebrating advances in commercial applications. "People here believed in the past that applied work wasn't well rewarded," Temkin says. Instead bonuses and salaries—and the psychological rewards of building a reputation—were coupled to such benchmarks as the number of papers researchers published in respected journals and the number of invitations they received to speak at conferences. "So the question is what to do with someone who does an applied project and doesn't publish anything for a year," he points out.

Such questions only begin a list of confusing and vexing issues that Bell Labs managers now face—issues that little in their previous careers has prepared them to tackle. Twenty years ago, Fleury recalls, the primary criterion for promotion into management was simply scientific prowess. Management training consisted of "sitting through a few days of management orientation and learning to deal with people," he recalls.

Now the job demands the equivalent of night vision. Midlevel manager jobs "are a nightmare," Penzias concurs. "The world that this manager interfaces with has changed enormously. The rules have changed," he says. Before the breakup of AT&T, there was a five-tier hierarchical structure above a young department head, and every manager was a technical leader. "Now the department heads are working for business people," Penzias states.

Managers now find they must continually be looking sideways to spot the product possibilities for research efforts. "It used to be, in the sequential days, you built something, and then someone else worried about it. You mailed it away. Today people are beating on you constantly," Penzias says.

These managers are also in the thick of reshaping one of the most delicate cultural issues at Bell Labs: the "star" researcher versus the team player. For decades, points out Paul S. Henry, director of the communications systems research lab, Bell Labs fostered stars. It hired the best and brightest young scientists, creating a fiercely competitive coterie of scientific Brahmans. That intellectual arrogance often translated into a fierce passion to prove a result—and so led to the classic Bell Labs breakthroughs.

But carrying an idea through devel-

opment requires a different sort of temperament, "someone who understands the universe is bigger than himself or herself," Henry says. The trick will be finding ways to blend different types of people. "Every lab should have one or two stars," he maintains. "But I think an important issue is: Will those people want to work at Bell Labs? How can I entice such a person to come to Bell Labs?"

Current staff members, meanwhile, are watching management for cues about the sanctioned balance between applied projects and their more free-form research. "Are you going to be punished [for doing applied projects] or allowed to go back to research?" Temkin asks.

Such ambiguities have gnawed at the fragile bridge of trust between researchers and managers. In years past, the researcher-manager relationship was relaxed, Fleury points out. Creative researchers were sheltered from distractions; department heads translated their work for the hierarchy above. "It's still true to a degree," Fleury adds, "but I don't think people trust their managers to represent them."

Critical to restoring that confidence will be convincing researchers not only that the research is important to corporate AT&T but that superlative science will remain a hallmark of Bell Labs. "We remain thoroughly committed to research into basic science as well as to the potential applications that are of benefit to humankind," declares John S. Mayo, who was appointed president of Bell Labs this past summer.

Researchers are "more worried than they need to be," Fleury insists. "People in research management are saying, 'It's not such a big deal, you have to trust us. We believe there's commitment for the long range.' But I don't believe that message is being accepted all the way down the line." It will take more than words to convey that message. Fleury hopes that once Bell Labs has endured a few budget cycles, researchers' confidence in their managers will grow.

The structural changes are completed, Penzias adds. As the dust settles, he hopes researchers will begin to believe in the new approach. "To say that we'll ever be totally happy, that I'm going to bring the 1950s back—sorry, I can't," Penzias says. Both he and Mayo argue that realigning research to include a stronger focus on customers will help spur more research of the type that led to the transistor and the laser. What remains to be seen is whether Penzias has adopted the right religion and whether he can convert the rest of Bell Labs. —*Elizabeth Corcoran*

Thinking of Machines

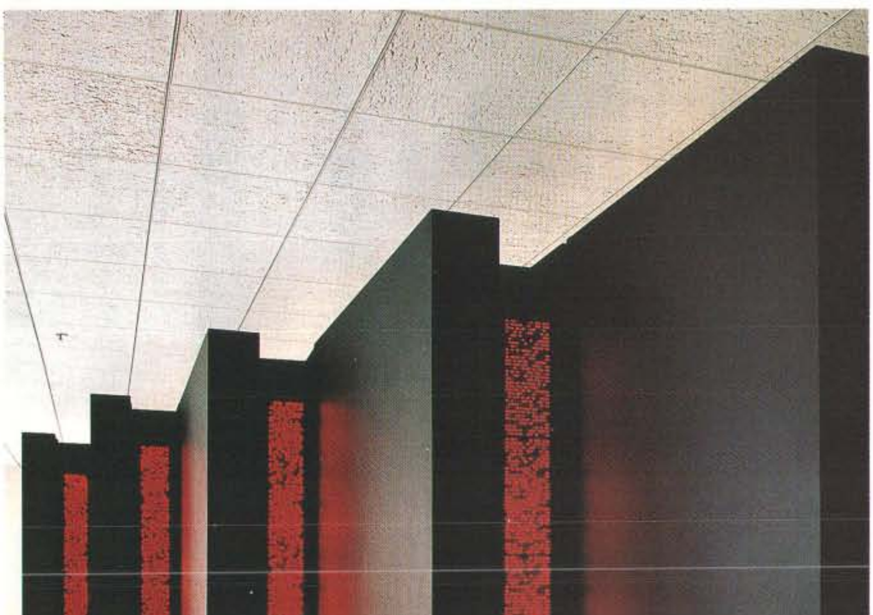
Hillis & Company race toward a teraflops

In 1981 a graduate student in Marvin L. Minsky's Artificial Intelligence Laboratory at the Massachusetts Institute of Technology wrote a curious memo. First he complained that computers were too slow: try to instill even a twinkle of intelligence in them, and they bog down even more, he said. Then he proposed a solution: a novel computer built by connecting thousands of weak processors.

Ten years and 450 employees later W. Daniel Hillis and his Cambridge, Mass., company, called Thinking Machines, plan to unveil his third computer based on that concept. This one, Hillis believes, may finally muster enough speed and grace to let him tackle artificial intelligence. According to Hillis, the raw processing speed of the largest version of this series of Connection Machines, dubbed CM-5s, could be as much as a trillion floating-point operations per second (teraflops)—a trophy eagerly sought by more than half a dozen of the world's leading supercomputer designers.

The models of the machine that Hillis was slated to unveil in late October will not reach a teraflops. But based on that design, Hillis says he can plug together about 16,000 processor nodes and "comfortably" calculate at the teraflops level. Thinking Machines has not yet priced such a machine, which would likely occupy an area as large as a tennis court. Smaller CM-5s will range from \$1.5 million for a 32-processor-node machine to \$20 million for an 8,000-node machine.

Like the first computer introduced by Thinking Machines in 1987, the CM-5 is a parallel processor—one that sets many computing elements to work on a problem simultaneously. The new design should further push so-called parallel computing into the mainstream, partly with the assistance of IBM, which recently gave a nod of approval to Thinking Machines in the form of a cooperative research agreement.



COMPUTERS should not look like refrigerators, Danny Hillis declares. This version of his new supercomputer uses 1,024 processor nodes. Photo: Steve Dunwell.

Yet whereas the early Connection Machines relied on thousands of relatively simple one-bit processing units, the CM-5 could use as few as 32 processing nodes. These nodes rely on a package of four accelerator chips, along with a sophisticated microprocessor, called a RISC chip, which runs fast by carrying out simplified instructions.

From a user's point of view, the CM-5 may also help bridge the two divergent schools of parallel programming that have developed over the past few years. The new architecture has been designed to let users take advantage of both SIMD (single instruction, multiple data) and MIMD (multiple instruction, multiple data) programming. Hillis had previously emphasized SIMD programming, in which one instruction is broadcast to all processors, which then carry out the operation on their own datum. Other designers have pursued MIMD, in which more complex processors use different instructions to manipulate different data sets. Although MIMD architectures can adapt more flexibly to a wider range of problems than can SIMD designs, they can be difficult to program.

During the past year or two, SIMD machines, such as those built by Thinking Machines and MasPar Computer in Santa Clara, Calif., have been gradually edging closer to MIMD designs, points out Jeffrey C. Kalb, president of MasPar. In the CM-5, every node can operate either on its own independent set of instructions (in an MIMD fashion) or on instructions broadcast to all processors (SIMD). Independently operating nodes are synchronized when necessary. Depending on the work at hand, processing nodes might undertake 10,000 operations without being synchronized—or communicate with one another at every step.

Physically connecting such processing nodes, however, is no trivial task. According to Hillis, researchers from Thinking Machines and from M.I.T. have created a network in which the amount of communication possible between processors increases at the same rate as that at which more processors are added. Hillis is still reluctant to provide precise details of the network that makes the machine so "scalable." Even though communication between nodes physically adjacent to one another will still be faster than between distant nodes, Hillis says that the precise geometry of the processors is far less important than it was in earlier Connection Machines.

The communications scheme is also

key to two other important features of the machine: its reliability and the speed with which it fetches or sends data to external memory banks (called I/O, for input/output). Almost a third of the circuits in the communications network are devoted to ensuring the machine is functioning properly. Should a processor fail, the machine will automatically reroute tasks and data, without significantly slowing down its speed, Hillis says.

Shuttling data in and out of an external memory is essentially an extension of the communications network used within the machine. As a result, multiple I/O ports, each of which can operate at about 20 megabytes per second, can be teamed to transfer data at hundreds of megabytes or even tens of gigabytes per second.

Hillis is betting that the SIMD/MIMD duality of his machine will open up new classes of problems that earlier models of Connection Machines did not handle well. By late November, when the first four CM-5s were scheduled to be working at customers' sites, users will have had a chance to answer that question for themselves. But first they will have to resolve some software problems. Because the architecture of the Connection Machine has changed, users of earlier models must recompile, or rearrange, their programs before the software can run on the new CM-5. "The single biggest problem the industry faces is developing software," declares Kalb of MasPar.

Thinking Machines' recently announced partnership with IBM might help boost its software reach. IBM has clients who need highly parallel architectures, says Irving Wladawsky-Berger, an assistant general manager for IBM's enterprise systems division. At the same time, "there is a class of customers for whom having it in a blue box with 'IBM' on the side is the solution. They need speed integrated to IBM," Hillis points out. Although the two computer makers do not plan to market their products jointly, they will develop techniques for moving customers' programs from IBM's 3090 series of mainframes to various Connection Machines.

Hillis is not planning to make any major changes in future architectures. "We've pretty much settled into the right general trend for parallel machines for the next decade," he says. Hillis himself plans to spend his time using the machine, particularly concentrating on artificial-intelligence applications. "Now," he adds, "we can't blame the power of the tools for not having a thinking machine."—*Elizabeth Corcoran*

Beyond Sympathy

Growth factors may help heal stubborn wounds

What sounds like a line from a country heartbreak song is in fact a serious medical problem for many people: some hurts never mend. Nonhealing wounds often afflict diabetics, whose loss of sensation in the limbs invites injuries the body cannot rally itself to repair. People with immune systems suppressed by toxic therapies or AIDS may also suffer ulcerations that refuse to go away, as do bedridden hospital patients.

For now, doctors have little save sympathy to offer, but biotechnology may soon provide something more tangible and effective. Growth factors—natural proteins found in high concentration at sites where healing occurs normally—show much promise for wound healing.

A *Who's Who* of biotechnology companies, including Genentech, Amgen, Chiron, Synergen, California Biotechnology (Cal Bio) and ZymoGenetics, are all developing various forms of these substances. So, too, are such major pharmaceutical firms as Merck, Ciba-Geigy and Bristol-Meyers Squibb, alone or as big brothers to smaller firms.

Growth factors are reinforcing scientists' understanding of healing as a series of steps because each appears to work at a different point in the process. A protein known as platelet-derived growth factor (PDGF) seems to kick off the healing cascade by recruiting infection-fighting cells. Others, such as fibroblast growth factor (FGF), promote growth of new blood vessels that supply local cells with nutrients and oxygen. Transforming growth factor-beta (TGFb) appears to work later in the cycle to spur deposition of a matrix where cells may cluster.

The names of the factors reflect the tissues from which they were first isolated, although researchers now know the proteins exist in small quantities in just about any tissue and also perform other functions. For instance, PDGF was recently found in the brain, far from platelets that course through the blood. "The names tend to stick pretty strongly, even if they're no longer that appropriate," observes Hugh D. Niall, vice president of research discovery at Genentech in South San Francisco, Calif.

Gauging which factor will be most effective for treating a particular type of wound "boils down to what you think is going wrong in that particular case of nonhealing," explains Judith A. Abraham, a molecular biologist and principal scientist at Cal Bio in Mountain View, Calif. "Once you know that a factor performs a particular function, you say, 'Okay, now let's go find wounds where that's a problem.'" Her firm is testing FGF in the treatment of pressure sores as well as diabetic and venous ulcers. All three are "microcirculation" disorders at the capillary level.

"There is enormous expectation that these factors are going to work, but there are still substantial hurdles," states Mark J. Murray, director of new business development at ZymoGenetics, the Seattle subsidiary of Novo-Nordisk. One will be proving to the scientific community and later the U.S. Food and Drug Administration that growth factors actually convey a therapeutic advantage.

"Quantitatively measuring wound healing is not a trivial matter," Murray says. He explains that nonhealing wounds often respond simply to the basic care of putting someone in a hospital, cleaning the damaged area and paying attention to it. Demonstrating that growth factors accelerate this regime's rate of healing is hard to do. Consequently, companies will not discuss publicly how much or how often they are giving the drugs.

Researchers are still trying to figure out the best way to deliver the proteins to the site where they are needed and keep them there long enough to be effective. "You need a formulation with sufficient viscosity to hold the growth factor in contact with the wound, but you don't want something that will bind and inhibit release of the protein," says Alan F. Russell, vice president of scientific affairs at Chiron in Emeryville, Calif. Chiron initially delivered one of its growth factors in a simple solution that was easy to make and assay, but it now uses a gel instead.

Companies are wishing for something that would bind and inhibit their competitors—patents, for instance. Only Synergen has been issued one so far, for basic FGF. The Boulder, Colo., firm is furthest along of any of the companies developing growth factors; it intends to seek marketing approval for FGF from the FDA in 1992.

As various growth factors become available, some researchers anticipate that they may be used in cocktails. Such combinations might speed postsurgical healing of immunosuppressed or even basically healthy individuals anxious to be released from hospitals. Others dismiss such a give-it-all-you've-got approach as overkill, an arrogant affront to the body's own miraculous ability to heal itself.—*Deborah Erickson*

Seeing Is Believing

A picture may be worth a million-dollar settlement

More often than not lately, a jury of one's peers can reach a verdict only by understanding how things work: how pressure can cause a valve to rupture, how an oil tanker navigates by radio beacon or how DNA fingerprinting can identify a suspect.

Responding to the need for crash courses in science, technology and medicine, trial lawyers have begun to give the average juror something to relate to: Television. Increasingly, the deftest attorneys in big-dollar cases are, through the use of computer animations, adding time and motion to legal exhibits presented as evidence. In an aviation case, for example, the jury may watch a precise computer-generated replica of an airplane up to the moment of impact.

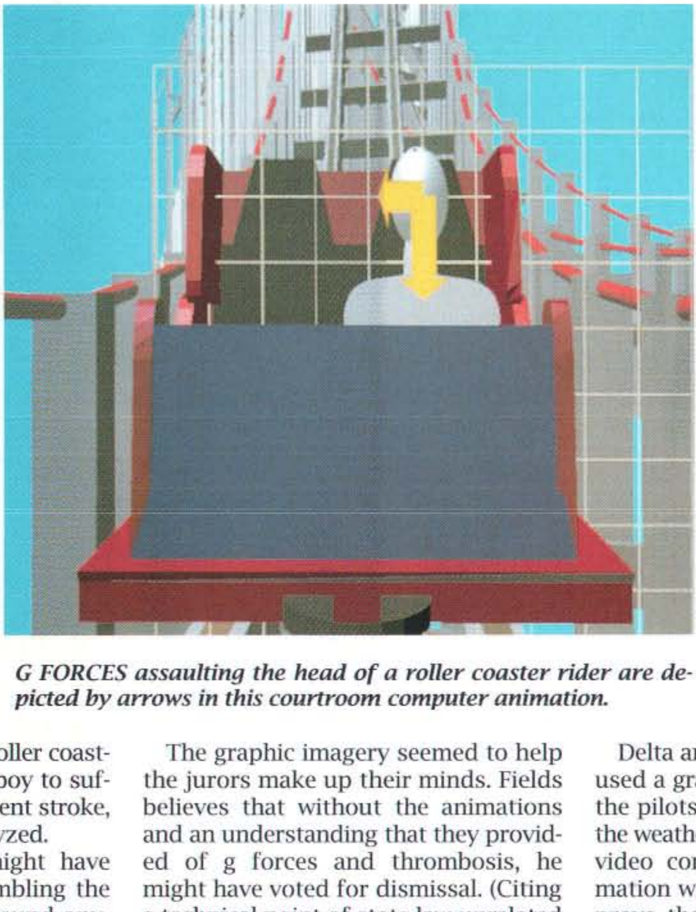
"This is like a third- or fourth-grade class when the teacher says it's time for a movie," says David W. Muir, senior vice president of Forensic Technologies International (FTI), in San Francisco. "These animations get the jury's, the judge's and everybody's attention."

In fact, computer graphics often receive good ratings in the jury room, even for seemingly implausible theories. Howard L. Nations, a Houston trial attorney, had to find a way to convince a Texas jury in 1989 that the buffeting of a roller coaster had caused a 16-year-old boy to suffer a torn artery and subsequent stroke, which left him partially paralyzed.

Nations knew that he might have a tough time. Nothing resembling the facts of the case could be found anywhere in the legal literature. And his opponent, the AstroWorld amusement park, was sure to point out that a stroke had never been experienced by the eight million riders that had paid their money to ride the Cyclone. (After the incident, however, the park owners changed the seat design.)

Nations took no chances. For $18,550, he hired FTI to make a 15-minute animation to back up the testimony of his three expert witnesses. The animation, which reenacted a portion of the ride, showed a faceless boy whose head was tossed from side to side by forces of gravity as the train raced down and around the Cyclone's precipitous inclines and hairpin curves. Arrows on a grid that was superimposed over the image of the roller coaster moved along the axes to show the magnitude of the g forces. Another animation went on to reveal how a blood clot from the boy's broken artery moved to the brain, where it caused a blockage that led to a stroke.

The 12 jurors, who shared memories of uneventful roller coaster rides, were initially skeptical of the claim, according to Howard H. Fields, a data-processing manager who served on the jury. Even so, they decided after two days of deliberation to award the boy $2.5 million.



G FORCES assaulting the head of a roller coaster rider are depicted by arrows in this courtroom computer animation.

The graphic imagery seemed to help the jurors make up their minds. Fields believes that without the animations and an understanding that they provided of g forces and thrombosis, he might have voted for dismissal. (Citing a technical point of state law unrelated to the graphics, the district court judge in Houston later ruled that the boy was not entitled to recover any money. Nations and AstroWorld then settled the case for an undisclosed sum, thereby averting an appeal.)

Although animated graphics have been used hundreds of times, they have largely been confined to cases where $1 million and often much more is at stake. The painstaking process of refining the graphics and animation can take a year's work and cost hundreds of thousands of dollars in fees.

One fear lawyers have is that a $100,000 animation will be crafted by a specialty graphics house only to be thrown out by a judge who is suspicious of computers and videos. An attorney must also expect the inevitable objections from an opponent that an animation distorts evidence.

Because of these caveats, most courtroom animations try to avoid visual dazzle or any overt appeal to jurors' sentiments by eschewing blood, corpses and likenesses of victims' faces. Animations are often introduced as demonstrative evidence, merely to illustrate the testimony of expert witnesses.

Graphics are ideally suited to aviation litigation, both because of the size of the claims involved and the availability of cockpit voice and data recorders. A graphic model of the plane can follow the exact flight path using yaw, pitch, roll and other data from the flight data recorder while also using the voice recorder tape as a sound track.

To defend the Federal Aviation Administration and the National Weather Service successfully against a negligence claim by Delta Airlines and others, the U.S. Justice Department turned to a computer-animated video, says Kathlynn G. Fadely, the lead Justice Department counsel in the case. The video showed the last moments of a Lockheed L-1011 airliner operated by Delta Airlines that crashed because of wind shear at the Dallas–Fort Worth International Airport in 1985.

Delta and its co-plaintiffs, which also used a graphic animation, charged that the pilots had not received warning of the weather conditions. The government video combined the black-box information with meteorologic data to help prove the pilots could see they were headed directly into a lightning storm and that the airplane's radar could have helped them avoid the foul weather. "If I were in a case that justified the cost, I certainly would use this technique," says Thomas Gibbs Gee, one of three federal judges (since retired) who heard an appeal of the nonjury case.

Going to court may be more and more like going to the movies. After an 18-month trial, what a juror or judge remembers best may be 15 minutes of cartoons. *—Gary Stix*

THE ANALYTICAL ECONOMIST

"All I Want for Christmas Is...."

By mid-autumn, Michael J. Boskin, who chairs the President's Council of Economic Advisers, had already made up his Christmas list. Privately and publicly he declared that he had just one wish: that the Federal Reserve would increase the money supply.

But much like the child who longs for a new pair of Nikes because he wants to be the star center of the school basketball team, Boskin yearns for action by the Fed to satisfy a subtler desire: he wants a perkier economy. What is unclear, economists say, is whether the government has the means to make that wish come true by Christmas—or whether it should even try.

Traditionally, the government has two instruments for influencing the behavior of the economy—fiscal policy and monetary policy. The first involves a decision either to spend money to encourage growth or to increase taxes to rein it in. Monetary policy is largely in the hands of the Federal Reserve, which can expand or constrict the money supply by changing the interest rate it charges banks that borrow money.

Trying to "fine-tune" the economy with these tools has always been a bit like trying to adjust a pocketwatch with chisel and hammer. What is more, after the government's spendthrift habits of the past few years, economists point out, with a note of smugness, that fiscal policy has become even more blunted than usual.

Fiscal policy is and under the current circumstances should be ineffective, states Charles L. Schultze, who chaired the Council of Economic Advisers in the late 1970s and is now with the Brookings Institution in Washington, D.C. Because the government has already run up the largest deficit in U.S. history—estimated to be almost $280 billion in 1991—it cannot spur growth by forcing increased spending.

If it tried to do so, argues Frederick C. Ribe of the Congressional Budget Office, the financial markets would likely respond by pushing up interest rates; such a reaction would effectively wash out any stimulus provided by a federal spending spree. "Spending more money now would prove that the government isn't serious about reducing the deficit," he points out.

Monetary policy should still work, economists say, but they debate precisely how effective it can be. Delos R. Smith, a senior business analyst at the Conference Board in New York City, argues that the atrophy of fiscal policy simultaneously weakened monetary policy. For instance, to increase the money supply, the Fed must push down interest rates. But lower interest rates may also dampen investors' eagerness to buy interest-bearing Treasury bills, which are needed to help finance the U.S. economy.

Even though lower interest rates should loosen up the flow of money through the economy by encouraging banks to lend and consumers to borrow (and to spend), both banks and consumers seem to be guarding their pocketbooks, Smith adds. Consumers may be waiting until they are convinced the recession is over and their jobs are secure. Banks, singed by debt-laden balance sheets, are scrutinizing loan applications more carefully. "The most optimistic outlook is that we'll have mediocre growth at best," he predicts.

Do fiscal and monetary policy have sufficient pizzazz to perk up the U.S. economy?

Schultze disagrees that monetary policy would be ineffective. "Interest rates, in real terms, are still very high by historical standards," he declares. "The recovery is faltering, as it did in 1971, when we had a mild recession and faltering recovery. But ultimately monetary policy can get us out of it," he adds.

The Federal Reserve could easily pump up the economy by increasing the money supply if it wanted to do so, concurs Herbert Stein of the American Enterprise Institute in Washington, D.C. Even fiscal policy is not choked by the current deficit, he suggests. "Who's to say the proper size of the deficit in a recession?" demands Stein, who chaired the Council of Economic Advisers in the early 1970s. Perhaps it should be $350 billion "and not a penny more." Then again, $400 billion might be palatable as well, he adds.

Nevertheless, for his part, Stein opposes efforts to stimulate the economy by any policy at this point. "This recession is very mild," he emphasizes, "just on the path of the average postwar recession. The economy doesn't need pumping." Those who complain that stimulation would be ineffective or even detrimental, he contends, are just "using that argument against doing what they don't want to do anyway."

Stein has unusual company supporting this view—namely, progressive economists. Samuel S. Bowles of the University of Massachusetts at Amherst, for instance, argues that blind reliance on manipulating market forces, such as the size of the money supply, has forced the U.S. economy into its current straits. Bowles calls for abandoning the "hidden hand" of the marketplace in favor of a more visible "handshake" among labor, management and capital.

Such cooperation, adds David M. Gordon of the New School for Social Research in New York City, might enable workers in the U.S. to spend more time doing productive work and less time simply supervising one another—a task that occupies 12 percent of the nonfarm work force in the U.S. but only 4 percent in Japan and 3 percent in Germany, Bowles observes.

What Boskin should want for Christmas, Bowles says, is for "the business community to give up its antiquated love affair with unregulated markets," so the government can pursue policy "unencumbered by archaic dogma." After all, he adds, not one of the U.S.'s international competitors labors under the illusion that economic growth requires enterprise to be completely free of governmental intervention.

Schultze offers a different Christmas wish: that Boskin will "tell his boss to stop yakking about capital gains." Echoing Stein's view that there is no cause for panic, he believes a gentle push from the Fed might now be in order. Should the Fed not act, the government might overreact and try to jump-start the economy through "an unholy alliance on the Hill—more spending, tax cuts for the middle class, capital gains tax." And that, Schultze avers, will be the economic equivalent of putting Pandora's box under the tree.

—Elizabeth Corcoran and Paul Wallich

A Short Trek to Infinity

Captain's log, stardate 2529.2: "The five-year mission of the *Starship Overambitious* is to invade strange, new worlds, to wreak havoc in new civilizations and to boldly go where *Starfleet* tells us. But mostly we run into space-dwelling zombies who think they can pulverize a starship. Just yesterday a cosmic caterpillar encased us in a gigantic cocoon. The critter was no match for our matter-antimatter loom, and we wove the cocoon into enough silk for the entire crew. We have set a course for—"

Red alert, red alert, whoop, whoop.

Startled, Captain Jonah T. Kink nearly fell out of his command chair.

"Good grief, what is it, Mr. Pock?"

First Officer Pock jumped to his console. "Captain, we seem to have encountered a strange, glowing region of space," he said, raising an eyebrow and wiggling his shaggy ears. "I am 99.357 percent sure that we have entered an Ideal Newtonian Field."

"What in blazes is an Ideal Newtonian Field?" Dr. Annoy exclaimed from across the room.

"Quiet, Annoy, or I'll send you back to suture the cosmic caterpillar!" Kink barked. "Go on, Mr. Pock."

Pock was born and raised on the planet Vulgaria. His mother was a Vulgarian, and his father was a Warthog. So Pock was half-Vulgar; some said more. "Captain, the red alert began as we approached a planet inhabited by extraordinarily intelligent aliens known as the Weelers. Their technology is so advanced that they can create entire universes, very different from our own. The Weelers seem to have captured us in a universe governed by the laws of Newtonian physics. The *Overambitious* is now traveling through an infinite, three-dimensional universe in which both space and time are absolute."

"You mean there's no relativity. Einstein would be horrified."

"A logical deduction, Captain. But the implications are much more alarming. In an Ideal Newtonian Field, a massive body may be nothing more than a point in space, and—excuse me, Captain. Sensors indicate a projectile heading in our direction."

"Put it on the screen, Mr. Pock. Evasive maneuvers, Mr. Flakeoff."

The projectile was picking up speed, faster and faster.

Whoosh!

Kink and his crew shook like commuters on a subway. "Lieutenant Yahoota, did you get a fix on the trajectory of the projectile?"

"The projectile was bearing 12 point 53 point 30, but then it suddenly left the universe."

"You mean it vanished?"

"Not exactly, sir. It reached infinity. It got there exactly 17.23 seconds after we detected it."

"Astonishing," Pock declared. "A phenomenon completely unknown to Humans or Vulgarians."

"The projectile consisted of a number of point masses," Yahoota added.

"Mr. Dott, what's your analysis?" The chief engineer, a Scotsman, studied his instruments. "Newtonian point masses, ah'd hazard a wee guess. Verra tiny particles, sur. Either Newtrons or Newtrinos, ah'm not sure which."

"Any evidence of unusual forces?"

"No, sur. Just the usual inverse square law of gravity."

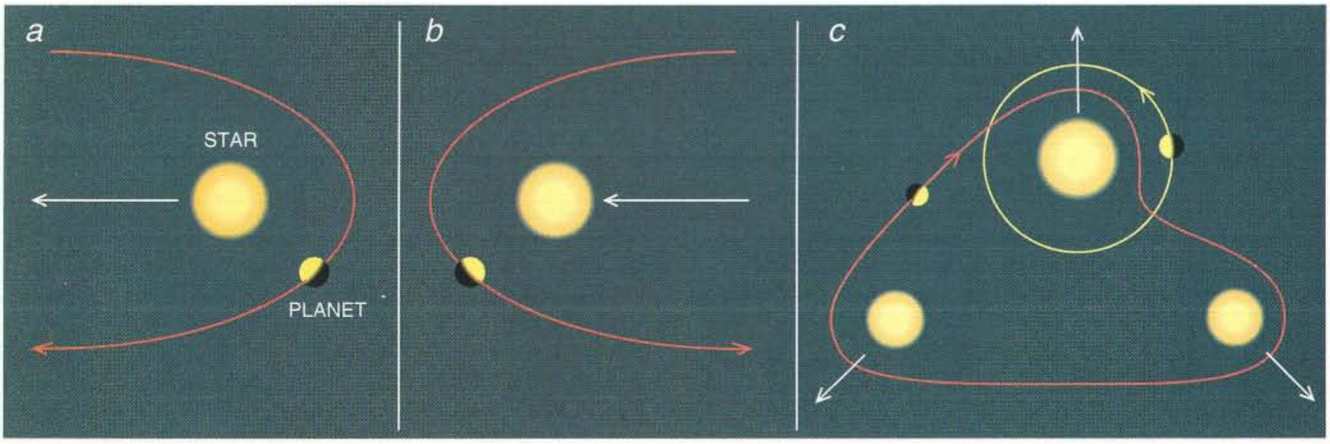
Mr. Pock punched a few keys on his computer. "Captain, the projectile flew away to infinity in a finite period of time, unaided by any technology, except for the Newtonian Idealization Field."

"But—that's impossible," Kink exclaimed. "A system of gravitating point masses can't just whiz off to infinity. It would violate the law of conservation of energy."

"Captain, that is unclear," Pock explained. "Any gain of kinetic energy might be compensated by a loss of potential energy. The masses can go faster provided they travel through an ever weakening gravitational field. Such a situation can arise if the masses continue to spread farther apart. Yahoota, did all the masses depart toward infinity in the same direction?"

"No, Mr. Pock, the masses essentially exploded in all directions," she said.

Kink persisted. "Well, in any case, the masses still can't get to infinity. That defies logic."



***SLINGSHOT EFFECT** speeds up a planet when it approaches a star in a direction opposite to the motion of the star* (a). *When a planet approaches in the same direction as the star is traveling* (b), *the planet will slow down, and the star will accelerate. Because of the slingshot effect, the celestial bodies in the configuration at the right* (c) *will accelerate in various directions. The system will expand to infinity in a universe where the laws of relativity play no role.*

Pock's ears pricked up at the sound of one of his favorite words. "Logically, Captain, that is correct. But in a certain sense, one can show that a particle will get to infinity if one deduces that the particle will pass beyond a sphere of any fixed size after an appropriate period of time." Kink looked perplexed.

"Captain," Pock continued, "think of a single particle traveling in a straight line at a constant speed. After infinite time, it will have removed itself from the interior of any finite sphere, effectively falling off the edge of the universe. Except, of course," he added hastily, "that one can't fall off the edge of an infinite universe."

"Naturally, Mr. Pock, I meant that the masses cannot escape to infinity in a finite period of time."

Pock waggled his ears, thinking deeply. "You are probably right, Captain. But a mechanism of sorts does suggest itself to me."

Mr. Dott snorted loudly. "Kindly enlighten us, Mr. Pock."

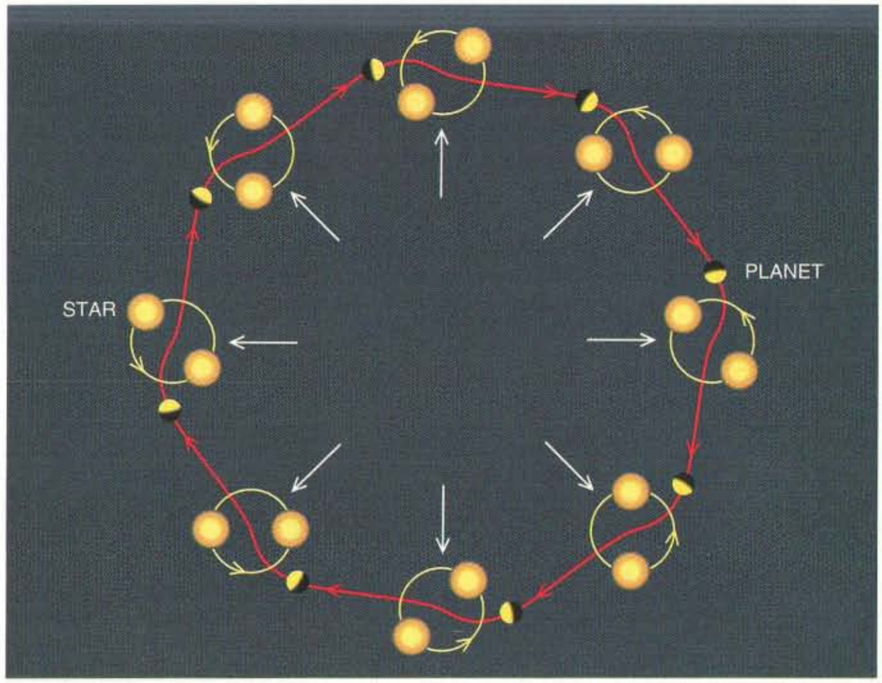
"If a particle accelerates rapidly enough, then it can travel an infinite distance in a finite time. Imagine that for the first second a particle moves at a speed of one meter per second. In the first second, it travels one meter. Now accelerate it so that for the next half-second, it moves at two meters per second, traveling a meter farther. Then continue in the same way, halving the time interval and doubling the speed, like this." With his *Starfleet* stylus, Pock drew up a table:

	Speed (m/sec)	Distance (m)	Total distance
First second	1	1	1
Next half second	2	1	2
Next quarter	4	1	3
Next eighth	8	1	4
Next 16th	16	1	5
Next 32nd	32	1	6

"After two seconds, the particle will have traveled an infinite distance—provided the velocity increases at a rate greater than that at which the intervals of time decrease. In other words, any particle will reach infinity if its speed increases geometrically over intervals that decrease geometrically. I call this Pock's Principle of Geometric Growth. The time required to reach infinity depends on the growth rates, but it will always be finite."

"But, Mr. Pock," Dott chirped, "that means the little devil must be able to travel faster than light."

"Yes," Pock said, "but I need not remind you that in an Ideal Newtonian Field, an object can achieve a velocity greater than light."



ANY NUMBER of planets and stars can escape to infinity if they orbit in such patterns as the one above. The pattern is based on a regular polygon, here an octagon. For each side of the polygon, there are two stars and a planet. Pairs of stars orbit around each vertex of the polygon. The planets travel from pair to pair.

Kink drummed his fingers on his chair. "Dotty, can we defend the ship against Newtonian point masses?"

"Newtron bombs would do the trick, sur. But our supplies o' those are verra limited. Just help me with one question, Yahoota. How many of those pointlike monsters passed us by?"

"Not sure, sir. Not very many. The events happened so fast, the instruments could not get a precise count."

"It cannot be just one body," the Vulgarian grunted. "Under Newtonian gravity, a single body—not influenced by any other forces—moves at a constant velocity in a straight line."

"So perhaps there were two bodies," Kink asserted.

"No, Captain," Pock said. "With two particles, the orbits would be either ellipses, hyperbolas or parabolas. Planets travel in elliptical orbits; comets from deep space move in parabolic or hyperbolic orbits. Planets in elliptical orbits cannot reach infinity at all—they remain bound to their suns. Comets can reach infinity, but they take an infinite amount of time to get there. Comets slow down as they get farther away."

"So how many of these blasted bodies are there?"

"Captain, we can rest assured," Pock stated, "that the Weelers would use the smallest possible number of masses. Their extreme efficiency is legendary. I'll call up the information on the ship's computer." Pock turned more knobs. "Interesting. It appears that the problem was first posed in stardate 1895 by the mathematician Paul Painlevé—"

"No need to read to us, Pock. Turn on the computer's speech synthesizer."

The computer spoke in a voice that sounded like Daffy Duck talking through a tin can. "Painlevé studied singularities: situations in which the laws of Newtonian physics break down. More specifically, a system can have a singularity at some instant of time if the solutions to its dynamic equations cannot be continued past that instant. The simplest singularity for a system of gravitating point masses occurs when two masses collide and occupy the same point in space. Besides collision, singularities occur when a mass reaches infinity in a finite amount of time. Such situations are known as hypersingularities."

"As I already explained," Pock added, "one or two bodies cannot possibly produce hypersingularities."

"Why, Mr. Pock," the computer cried, "you are so intelligent I would kiss you if I could." The Vulgarian blushed.

"Computer!" Kink barked. "Quit flirting with Mr. Pock and get on with it."

"Painlevé proved that three bodies cannot generate a hypersingularity, but he could not extend his result to four or more bodies. Painlevé recognized two varieties of hypersingularities. One

kind occurs when a body flies off to infinity along a simple trajectory. The other kind involves a body that starts to oscillate ever more wildly as time approaches some particular value. In the 20th century Hugo von Zeipel of Uppsala University in Sweden, Richard P. McGehee of the University of Minnesota, Donald G. Saari of Northwestern University and Hans Sperling, then at Boeing Aircraft in Huntsville, Ala., proved that any system that generates one type of hypersingularity must also produce the other kind. In other words, some bodies must travel to infinity and oscillate wildly."

"Tell me more about these hyperwhizzes and wobbles," Kink demanded.

"Saari demonstrated that a hypersingularity can arise from four bodies. But if the speed, position and mass of those bodies are chosen at random, then the chance of a hypersingularity is nearly zero. John N. Mather of Princeton University and McGehee did discover a hypersingularity in a system of four bodies confined to a line—but only after an infinite number of collisions, assumed to be followed by elastic bounces. Then, in stardate 1984, Joseph L. Gerver of Rutgers University came up with a scenario that allows five bodies to escape to infinity. Let me show you what Gerver discovered."

The computer began projecting images on the main screen. It showed three stars, one bigger than the others. They were arranged in a triangle, with an obtuse angle at the heaviest star [*see illustration on page 100*]. "Remember, the mass of these bodies is confined to a point. Their size on the screen represents just their relative mass."

An asteroid appeared in an orbit around the outside of all three stars, approaching them very closely. Each time the asteroid passed the most massive star, it picked up speed by the so-called slingshot effect. The asteroid gained gravitational energy from the star, whereas the star's energy decreased by the same amount. On subsequent encounters with the other two stars, the asteroid transferred energy to them by a reverse slingshot. As a result, the speeds of the asteroid and the two less massive stars were increased.

"In this system the law of conservation of energy prevents the heaviest star from speeding up, too. As a consequence, none of the objects escapes to infinity after a finite period of time. But Gerver found a legal loophole."

The computer displayed a fifth body, a planet that orbited the most massive star. Now as the asteroid whipped past both planet and star, the planet began to lose energy—so much that the massive star began to gain some. On each circuit of the asteroid, the stars and asteroid sped up, and the planet slowed down, spiraling in closer to the star. The energies balanced, and the triangle began growing geometrically fast. In a finite period of time, all three stars escaped to infinity, taking the asteroid and the planet with them!

The computer continued: "Gerver observed that although this scenario is plausible, the calculations needed to prove that it really works become so messy that the proof cannot be brought to a conclusion. Then, in stardate 1989, Gerver used an idea suggested by Scott W. Brown, now at Indiana University, to prove that a number of bodies, n, can escape to infinity if n is large enough. The configuration used is a more symmetric version of the triangle of stars and consists of any number of pairs of binary stars, all having the same mass."

The computer displayed eight pairs of stars, each pair making a circular orbit around its center of mass [*see illustration on preceding page*]. The centers occupied the vertices of a regular polygon with eight sides. The same number of planets were moving approximately along the edges of the polygon. The planets all had the same mass but were much smaller than the mass of the stars. Each time a planet approached a binary star, it gained kinetic energy via the slingshot effect. The binary star compensated by losing kinetic energy and moving to a tighter orbit. The planet also transferred momentum to the binary star, causing it to move outward, away from the center of the polygon. Because of symmetry, all eight pairs of binary stars were affected in exactly the same manner at exactly the same time.

The computer began to animate the celestial bodies. At each stage, the polygon grew; the planets moved faster, and the binary stars closed up into tighter orbits.

Mr. Pock grabbed the controls of the computer like a Vulgarian child. "Wow! Let me try!" He leaped up and down in his seat until he saw the captain's stony glare. With effort, he controlled his enthusiasm.

"Captain, the entire system does appear to escape to infinity after infinitely many slingshots, which occur ever more rapidly during a finite time," Pock said. "A computer simulation is not a logical proof, however. It is necessary to demonstrate that suitable initial conditions will indeed produce the correct sequence of events." He thought for a moment. "Symmetry should play a role in the proof. It effectively reduces the problem from $3n$ bodies to 3. Once you have determined the positions and velocities of one binary star and one planet, symmetry determines those of the remaining bodies. In other words, the problem reduces to one about three disconnected 'bodies'—each a regular polygon of point masses—moving under a very complicated set of forces. But it still looks like a rather intractable problem to me," Pock said.

"A proof that would satisfy the most hairsplitting brand of logic can be found for large enough n," the computer remarked, "because the forces simplify in that case."

"Blazing galaxies, all I want to know is, how large must n be?" Kink asked.

"Gerver did not determine the precise value," Pock answered.

"Confound it!" yelled the captain of the *Starfleet* cruiser. "Can't anyone give me a simple answer?"

"In stardate 1988 Zhihong (Jeff) Xia, then at Northwestern, proved that there is a way to make five bodies escape to infinity in finite time. His scenario is different from Gerver's, but it also involves symmetry."

"At last," Kink sighed. "So five point masses are enough."

"And four almost certainly are not," Pock said. "Because the Weelers always use the optimal means to achieve their ends, the projectile must have consisted of precisely five bodies."

"Good. We certainly have five Newtron bombs lying around. Now all I need to figure out is what the Weelers are up to. Why have they captured us in an Ideal Newtonian Field?"

"Captain!" Yahoota glanced worriedly over her shoulder, while her fingers continued to rap a keyboard. "The *Overambitious* is being pulled by the gravitational field of a complex system of nearby stars. Our speed is warp 1 and growing. Captain, it's increasing geometrically over geometrically decreasing intervals of time. Warp 2!...4!...8!...16!"

Kink turned to his helmsman. "Mr. Flakeoff, fire the Newtron bombs before we all disappear into infin—"

FURTHER READING

A POSSIBLE MODEL FOR A SINGULARITY WITHOUT COLLISIONS IN THE FIVE BODY PROBLEM. Joseph L. Gerver in *Journal of Differential Equations*, Vol. 52, No. 1, pages 76–90; March 30, 1984.

THE PROBLEMS OF MATHEMATICS. Ian Stewart. Oxford University Press, 1987.

THE EXISTENCE OF PSEUDOCOLLISIONS IN THE PLANE, preprint. Joseph L. Gerver. Rutgers University, 1990.

Science Books for Young People

The Salamander Room, by Anne Mazer. Illustrated by Steve Johnson. Alfred A. Knopf, 1991 ($13.95).

Brian is a little boy who came on an orange salamander crawling through dried leaves in the woods. He carefully carried the small creature home to his own room.

We do not see Brian's mother, but we hear her serious questions. "Where will he sleep? Where will he play?... He will miss his friends.... How will you feed them?... Soon there will be bugs... everywhere.... Where will the birds and bullfrogs live?" and after many answers, "Where will you sleep?"

Brian considered each question thoughtfully and gave his answer. He imagined one by one every need of a little orange animal. By the end, Brian had turned his bedroom into the forest itself so that the salamander might be really at home. "I will sleep on a bed under the stars, with the moon shining through... the trees; owls will hoot and crickets will sing; and next to me, on the boulder... resting on soft moss, the salamander will sleep."

The strength of its web of inferences and the tenderness of its simple words and effective paintings elevate this quiet book to poetic stature. Most of the 20 pages present only a few lines of text within the glow of woodlands color. Any boy or girl old enough to imagine bringing a salamander home can enjoy and learn from this book, either by reading it or being read to, most likely many times over.

Explorabook: A Kids' Science Museum in a Book, by John Cassidy and the Exploratorium. Palo Alto, Calif., Klutz Press, 1991 ($16.95).

Kids don't have to open this chunky book to see how different it is. A magnet encased in clear plastic is tied on, and on the front cover is a spinner with a moiré pattern. You can turn it slowly through dazzling gyrations of shifting color, easily understood after one careful look. That look is encouraged and explained inside on page 84. "Please do not simply read this book.... It is a tool." It is a book for people who tend to sit at the back in science lectures, and it puts the experience where it belongs, in your own hands, along with the words that help tease experience apart.

Seven sections go with the stuff you need, right on hand in the book. Lively pages tell of 50 cool and funny things to do with it all. We mentioned the magnet, which can also be a compass and the main part of an antigravity machine. Next comes a plastic sheet made into a magnifier good enough to read the dozen comic pages of Batman and Robin reduced to one single book page. Then come a couple of packets of agar, enough to plant sugary microgardens to host living bacteria and fungi. "Ready for your guests. But where are they?... The question should be, 'Where aren't they?' Take your mouth, for example. It's disgusting. A teeming, rich bacterial breeding ground... you can see for yourself," and do it safely.

A plastic grating for making rainbows follows, and then a flexible silvery mirror. A section on homemade science lets you improvise experiments with flowing air from your own hair dryer. The pages are full of photographs and cartoons that explain the experiments clearly. One of many optical illusions shows Elvis looking much more natural upside down than right side up (why?); another is a hard-to-believe perspective illusion about the short and the tall. The final exam is a photograph of a Russian cosmonaut. He is suited up and out in space. "I'm lying somewhere in this caption. Where?" the author admits. It all looks okay, but the daring cosmonaut in that bulky suit is named Svetlana Savitskaya, and "she is a mother of three."

John Cassidy is the author of 20 Klutz guides on juggling, bicycles and plenty of other kinds of "flying apparatus," all in his easy, flip and candid style. Now he has linked up with the savvy staff of the Exploratorium, that wonderful museum of science, art and perception in San Francisco. But near or far from the Golden Gate, this active, "ouchless" book is a find for boys and girls as well as their parents.

Fly the Hot Ones, by Steven Lindblom. Houghton Mifflin Company, 1991 ($16.95). **Ballooning: The Complete Guide to Riding the Winds,** by Dick Wirth and Jerry Young. Random House, 1991 ($22.50).

A talented writer in love with flying, Lindblom takes the reader up with him in seven different aircraft he actually flew (he describes one more, carrier-borne). The smallest of them was a Quicksilver Sport Ultralight, all aluminum tubing and gleaming fittings, a dozen indispensable flying wires tensed under its high red sail-wing like some "weird mechanical insect."

Its snowmobile engine lifts you and your five gallons of fuel to 2,000 feet, where you can fly "around the patch" at 60 m.p.h. You can't help laughing: you see no part of the airplane below you or in front of you, "nothing but air." (Judge final height for touchdown from the texture of the grass you glimpse between your feet.) You land thirsty, dried out by the steady blast of summer air. Next day you recall the magical hour a little dreamily; were you borne aloft in an enchanted lawn chair?

The upper edge of this pilot's envelope is the warlike Fighting Falcon, F-16, a single-seat dogfighter, hot rod of the missile-carrying world. You don't hop in with street clothes; even flying boots and fireproof coveralls are not enough. You need the G suit with the inflating air pouches that keep your blood and stomach from "running down into your legs," a torso harness, helmet and oxygen. (Ambient pressure falls and g's pile up quickly in an F-16.) This plane is dynamically unstable for maneuverability, life and death for a fighter plane, but its fly-by-wire computer frees the pilot from details and will override any stupid move. Its joystick movements so small you forget you make them, an F-16 "challenges its pilots to fly... at their limits—and a little beyond." Afterburner full on, this torch will stand on its tail, rising without winglift for a few seconds, "gone ballistic!"

Takeoff in a Piper Cub allows an introduction to the basics of piloting. Square loops and chandelles are explained around a little red-striped aerobatic Pitts biplane. "The most surprising thing is not how different they all are, but how much alike." Learn to fly whatever you can, but don't start flying too late, the author sings in siren song.

The second book is focused on the modern hot-air balloon, kept aloft by propane burners whose thermal power output compares with a jet engine's. These big pages are extravagant with colorful images of graceful balloons floating in air. Text and graphics convey a wealth of varied information. The history and prehistory of ballooning, the records of the balloonists, their finances and organizations, and a readable summary of present technology and how it grew are related by these two British participants. The growing point is now in Britain; even in the U.S. British balloon makers are very active.

The present era of the hot-air balloon opened with its first man-carrying free flight over Nebraska in 1960. Ed Yost came to the design obliquely, via his experience with unmanned helium-filled polyethylene balloons sent afloat over the Iron Curtain in the 1950s for high-altitude photography. His prototype burner, fitted with a preheated coil for evaporating propane fast enough without freezing the fluid, anticipated what is now standard in many sizes. A typical balloon to lift three or four people has the volume of a good-sized house, a 40-foot cube. In 1990 balloon and basket cost $15,000 new and $35 for each hour in the air (mostly for propane, if you can persuade friends to fill the chase crew).

Fabric is the second key technology here. The yarn is nylon or dacron, the weaving and pieced-together fabrication old and well-developed arts. A polyurethane sealant is essential, although its additives and layers are a matter of design choice. Color is now found everywhere.

The many-sided nature of this playful technology is well shown: balloons alone and in gaudy flocks, along the Rio Grande or over the Serengeti, advertising blue jeans and ice cream cones, skimming streams. Young readers are at real risk of seeking balloon passage, and a few of them will become pilots. The dream of floating around the world is still unfulfilled.

As the Crow Flies: A First Book of Maps, by Gail Hartman. Illustrated by Harvey Stevenson. Bradbury Press, 1991 ($12.95).

Better than its promise, this is in fact a first book on mapping, on purpose and process, not on product. We travel, a line of text to the page, from mountain slopes where the eagle soars to the garden where the rabbit hops. We visit the window boxes of the city, where the clever crow stops, and trace the path of the policeman's horse not far from the merry carousel. At last we follow a gull as it flies over the harbor and out to the lighthouse. The illustrations are broad and clear. None of them has map symbols, but instead they draw all that is named. Once we realize that the moon shines on all these places together, the entire route is assembled into one. It is not to scale, not done in plan, but interpretable as a big, easy pictorial map, the topology of a trip that the youngest readers and even those read-to will puzzle out delightedly.

Creepy Crawlies: Ladybugs, Lobsters & Other Amazing Arthropods, compiled under the direction of the British Museum (Natural History). Sterling Publishing Company, 1991 ($14.95).

The crawlies were the topic of a special exhibition, intended for schoolchildren, at the British Natural History Museum. The exhibit and the book alike were produced "with the help of many people." The book opens rather stiffly with a definition or two. Quickly a few colorful pages show us an album of animals, and a double spread presents a big crab in its suit of armor. If you lived inside a suit of armor, how would you grow? A dazzling page then displays no less than eight similarly shaped, successively larger skin molts of a crab. Other routes of development are summarized visually as well.

We admire colors and their origins, most unexpectedly the beautiful blue glow of New Zealand fungus gnat larvae. They shine to draw their prey toward sticky flytrap threads that they string from the roof of a dark cave. Naturally, some big, gross photographs are here, too, an anopheline mosquito attacking a hairy forearm, a feisty city cockroach, a busy covey of "biscuit beetles" (who prefer dry crispy treats to chocolate-covered ones). We miss an

aerial photograph of a big locust swarm, although good close-ups are here.

The book closes with an account of ancient arthropods, an unusual overview of the fossil record of the creatures. Trilobite models are compared with a modern pillbug, and we view elegant insects in amber and a painting of the greatest of fossil insects, a forest dragonfly with a 32-inch wingspread.

A couple of hundred choice color photographs sample this ark pretty well, but the final page is a clinching statement of biodiversity and its scholars: an entomologist is seen at his microscope in the Natural History Museum. He is backed by a high wall of narrow drawers, all labeled, and the giant tabletop is utterly covered by a hundred large paper trays filled with neatly pinned specimens to the edge of our view.

ALL ABOUT WHERE, by Tana Hoban. Greenwillow Books, 1991 ($13.95).

Two dozen color photographs, mainly scenes in and around Paris, form this book. Text is to be found on none of them, but the pages are so cut that no matter which page you have opened to, you can read the same list of words at the margin of the photograph. They are 15 prepositions right out of the grammar books, above, on, behind, under, out...below, over, around. Each of the scenes, all of them interesting to children, has been subtly chosen to evoke thought about spatial structure: a cat beyond a red bicycle in the grass, a tourist boat and its reflection passing under a bridge over the Seine, a rope lashing around a pile, a toy boat in a bottle, a small dog carried in a jacket pocket. The point is not simple exemplification of any straight-ahead definition, but a many-sided visual stimulation of the uses and pleasures of thinking about this space we all inhabit. The book is probably addictive for many a young person now growing toward reading and richer speech.

AN OWL IN THE HOUSE: A NATURALIST'S DIARY, by Bernd Heinrich. Adapted by Alice Calaprice. Illustrated by the author. Little, Brown and Company, 1990 ($14.95). **BATMAN: EXPLORING THE WORLD OF BATS,** by Laurence Pringle. Color photographs by Merlin D. Tuttle. Charles Scribner's Sons, 1991 ($13.95).

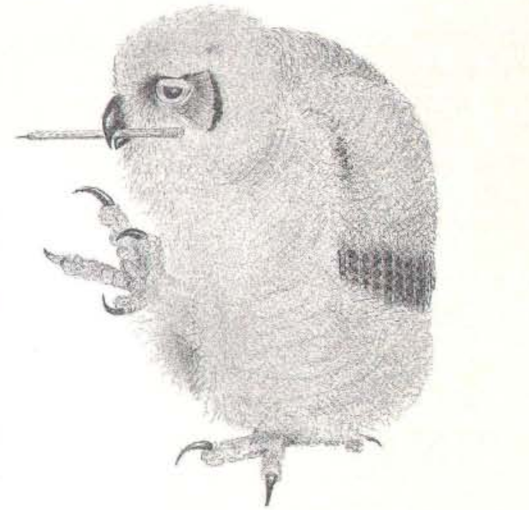
"A few years ago I did something I probably shouldn't have done," naturalist Heinrich begins. He adopted a fledgling baby great horned owl that he found in the spring snows. This expressive diary of what happened then to owl Bubo and to the zoologist is deftly adapted for budding naturalists.

A great horned owl is a fierce predator, with wings that spread close to five feet when mature. But it begins as a helpless woolly owlet. Little Bubo grew very fast indeed on meat fragments fed by an admiring host. Heinrich never hardened his heart, as the old falconers could, to keep avid Bubo hungry enough to learn to hunt for himself. Bubo developed a genuine fear of the family cat but would attack people, or at least their shoes. He lived for a time in the house, then he was boarded out in a center for injured birds (where incorrigibly dependent Bubo could win no black belt for hunting). Finally, he moved to a big outdoor flight cage, from which he was at last freed to fly the Maine woods, still boarding with the Heinrichs (he posed very stylishly on their Beware of Owl sign!).

In his second autumn, Bubo left for good, at last his own bird. It may be that he is the fierce-looking great horned owl that tamely posed for a photograph on a porch railing three years later, elsewhere in Maine. The book is a model of sensitive observation enchantingly conveyed.

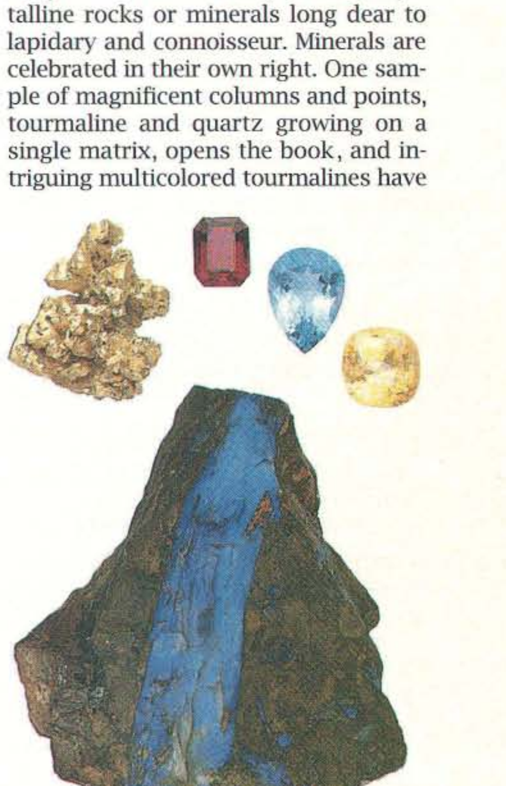
The second book, much less intimate, tells the tale of another naturalist, Merlin Tuttle (no connection with the Batman of DC Comics). Young Tuttle at 10 learned "with a passion" all he could about the mammals of California, where his father taught biology. The mammal buff promptly failed fifth grade! But his wise teachers let him go on anyway. In high school he proved by banding that the gray cave bats near his home were migratory. Past a Ph.D. in zoology and many research papers on bats, he finally decided that his career must be to change people's unthinking antagonism to bats. This attitude presents a growing threat to our fascinating and beneficial little cousins, with us the mammalian masters of the air as dolphins are of the sea.

In Dr. Tuttle's wonderful photographs we see bats worldwide, one at a time close up or flying in massive swarms, fishing and frogging and catching scorpions, even pollinating the blossoms of the giant saguaro cactus. A new bridge in downtown Austin, Tex., became summer home to a million free-tailed bats, the largest urban bat population in the world. They eat 15 tons of insects each night, a contribution to human health and the quality of Austin life that far outweighs the overstated danger from rabid bats. Tuttle helped found Bat Conservation International about 10 years ago; his work, and readers' pleasure, continues. The book's author, Laurence Pringle, is an old hand at first-rate books like this one for young readers.



CRYSTAL AND GEM, written by R. F. Symes and R. R. Harding. Special photography by Colin Keates. Eyewitness Books, Alfred A. Knopf, 1991 ($15).

The insipid tan of the instructive boulder is only skin-deep; a window let into it by a grinding wheel discloses a pearly lavender touched by green, the inner beauty of a fine specimen of Myanmar jadeite. Around it the page spread glows with carved jades and with lapis lazuli, turquoise and malachite, all microcrystalline rocks or minerals long dear to lapidary and connoisseur. Minerals are celebrated in their own right. One sample of magnificent columns and points, tourmaline and quartz growing on a single matrix, opens the book, and intriguing multicolored tourmalines have



a page of their own as well. The book does not forget homelier crystals, ice and aspirin, silicon chip and diamond saw blade, although gemstones and museum specimens clearly steal the vivid show.

Atomic order is lightly discussed, without using mathematics and based largely on the phenomena—models of form, angles between real faces and cleavage. Growth, both natural and synthetic, is treated quite fully. Alchemy, birthstones and other lore are presented well, although the healer in Taos, who cures by the laying on of stones, seems marginally acceptable placed beside piezoelectric oscillators. The crystal balls shown later would have been a more apposite context.

This is one excellent member of a long stream of one-design books, each leading a young reader to follow its broad theme through a surrogate museum. Spread after spread bears a montage of related images, in sharp color on a white ground with a concise text for each picture, like the labels in a museum case. It is the Museum of Natural History in London that holds most of the real three-dimensional objects we see here in the flat.

HIDDEN INSIDE, by Kim Taylor. Delacorte Press, 1990 ($9.95).

Looking inside is a mainspring shared by science and children. Kim Taylor is a photographer of prime curiosity, most adept with eye and lens. Among the dozen intimate close-ups within nature he has given us are the inside of a mussel, containing a few pearls and a rosy pea crab, and a minute young froghopper within the froth it has blown for shelter and defense out of a buttercup stem. A tree cricket is pictured out of focus, whereas a tiny if upside-down view of the same cricket is imaged sharply by a single polished raindrop that hangs from a rosethorn in the foreground. The last picture shows a fat, furry cat backlighted; superimposed is an exciting X-ray image of her unborn kittens hidden inside. Can the young reader count them?

ANDY GOLDSWORTHY: A COLLABORATION WITH NATURE, by Andy Goldsworthy, with 120 color photographs by the author. Harry N. Abrams, 1990 ($45).

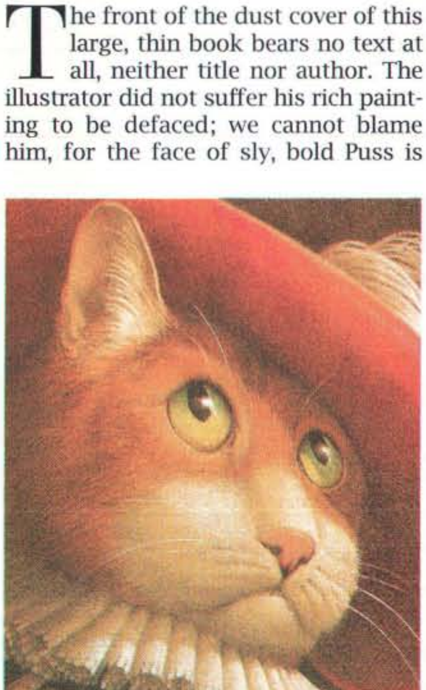
Bower birds do all they can. Playful children arrange the materials they find in impromptu ways. But this artist, who comes to woodland, mountain meadow or snow crust without tools or materials, transcends with hand and mind the bluest of bowers and the happiest of accidental art.

A golden ring, dandelion blossoms pinned with thorns to willow stalks, floats on forked sticks above a patch of bluebells in a Yorkshire park. Pebbles around a hole are subtly graded in color from white hole edge to gray rim, the central shadowed hole itself blacker than any pigment. Three big hollow snowballs open their interiors to us: sky-blue. Five outlines of the artist are clear, made by lying down in rain or snow to wait until the ground was "wet or covered before getting up." A strange ideograph drawn in green iris blades pinned together by thorns floats on the pond, enclosing five red rafts of rowan berries: "difficult to keep all the berries in, nibbled at by ducks."

A British artist, Goldsworthy has worked since his student days with whatever materials nature provides to create a transient order we can share through his direct, admirable photography. No primitive, he makes tools part of his life and work; he relies on the camera, but it was the freedom of using "hands and 'found' tools" that caught him. He has newly entered the more social domain of excavated earthworks at larger scale. This volume is a treasury of surprises; in no way aimed at children, it will reach them all.

PUSS IN BOOTS, by Charles Perrault. Illustrated by Fred Marcellino. Translated by Malcolm Arthur. Farrar Straus Giroux, 1990 ($14.95).

The front of the dust cover of this large, thin book bears no text at all, neither title nor author. The illustrator did not suffer his rich painting to be defaced; we cannot blame him, for the face of sly, bold Puss is striking, crafty green eyes atilt as his plumed hat, white whiskers picking up the lacy ruff of his collar. On the final page hangs a full-length portrait of Puss in Boots, the great lord pictured in heavy gold frame on the brocaded wall to astonish the little liege mice. The frontispiece within is a masterful view of the mill where it all started around 1700, lantern pinion driven by the great wooden cogwheel on its heavy wooden shaft, shaft tip and main bearing plate in hard stone. It is like a plate from Diderot's encyclopedia done in color.



Puss began clothed only in cat's fur, a mill mouser of no social standing. We watch his insolent rise through the confidence games he plays on a few dull peasants, on the fatuous monarch and on the richest of titled ogres (who dines, it seems, on a mess of serpents in a covered silver dish). Puss deceives them all, to match the lovely princess to the miller's youngest son (the man who first bought Puss the indispensable boots). Perrault's famous gloss on an old popular tale is told as a splendid, funny, cynical parable of the way the wicked world wags, possibly not only during the Old Regime. The translator has played his part well, too; the very first task Puss undertook in Boots was to entrap a young rabbit "who hadn't caught on to the ruses of this world." This book wins any good reader by its flawless artistry.

THE RIDDLE OF THE ROSETTA STONE: KEY TO ANCIENT EGYPT, by James Cross Giblin. Thomas Y. Crowell, 1990 ($13.95). **THE ROSETTA STONE: FACSIMILE DRAWING WITH AN INTRODUCTION AND TRANSLATIONS,** by Stephen Quirke and Carol Andrews. Harry N. Abrams, 1989 ($14.95).

The most important code-cracking occurred during the century it took to learn how to read Egyptian hieroglyphics. The century opened in 1798, when the Army of Napoleon won Egypt for a short time. About a year later soldiers of the French army, digging in an old fort at the mouth of the Nile near a town called Rosetta, came on a black slab of rock the size of a small tabletop. When they sent it to Cairo, where the scholars who had been brought along in the invasion worked, "the experts became tremendously excited." The stone bore three inscriptions: one in the sacred hieroglyphics no one had been able to read for 1,500 years; one in a later simplified form of that sacred writing; and the third, with the same message, in Greek, dated 196 B.C. and easy for the scholars to read. The Rosetta Stone indeed became the

key to ancient Egypt, but it was not an easy key to turn.

James Giblin briefly recounts the opening of the decipherment, with examples and good humor, in language well suited to readers and code writers in the middle grades. The Quirke and Andrews work is a tougher challenge, for serious code breakers in high school and up. Those authors have prepared a careful, full-sized drawing of the Rosetta Stone just as it is now in the British Museum. (The stone went off to London, not to Paris, when the tide of war turned against Napoleon.) That drawing accompanies the book as a poster more than three feet square, splendid for the wall. A brochure includes a full modern translation of each of the texts and a concise scholarly summary of the long history of the decoding.

Can you find the clues Thomas Young saw in 1814 that begin the story? The deeper ones Jean-François Champollion used to read out the old text are here, too, but the task is far from simple, even with hints.

THE RESTLESS EARTH: THE SECRETS OF EARTHQUAKES, VOLCANOES, AND CONTINENTAL DRIFT IN THREE-DIMENSIONAL MOVING PICTURES, by François Michel and Yves Larvor. Viking Penguin, 1989 ($15.95).

Lava pours from a whole molten lake, the city of Anchorage trembles scarily as seismic shocks pass, and the San Andreas fault slips northwest until Los Angeles is offshore from Mount St. Helens. Each world-shaking event requires only pulling a small tab to move the clever paper cuts and folds held between doubled pages. Of course, this is all down at map scale, where harmless change is very fast indeed. The simple and colorful maplands will show middle graders the main movements of seismology and plate tectonics. The novel sight of real motions within a map does make its point strongly. You can reverse plate drift, too, even the grand collision that raised the high Himalayas when India went crashing up into Asia at the breakneck speed of inches per year.

THE GREAT DINOSAUR MURAL AT YALE: THE AGE OF REPTILES, by Vincent Scully, Rudolph E. Zallinger, Leo J. Hickey and John H. Ostrom. Foldout in color. Harry N. Abrams, 1990 ($19.95).

In 1942 the Great Hall of the Peabody Museum of Natural History at Yale looked to the museum director like a "dismal, barren cavern." Its flat plaster walls boxed the wonderful skeletons of dinosaurs, small and large, without color or excitement. So in that wartime year the director engaged a young Yale painting student, Rudolph Zallinger, to undertake an ambitious mural, a huge illustration of the great creatures as they might have been in life, set amid the plant and animal communities of their long reign. The scene opens with the first of all trees. Lizard centered for 300 million years, the cast of players then changed with a bang, after a reptilian run twice as long as the entire history of our mammalian kind.

A dozen full-page panels in excellent color reproduction fold out of this small book to display the famous mural. In life it covers a wall 110 feet long, in a band 16 feet high, setting it among the largest paintings in the world. The mural was carried out in a painstaking layered and overpainted technique on dry plaster—*fresco seco* in Italian—apt for intricate detail and wide range of enduring pigments, once chosen for like reasons to emblazon the Sistine ceiling itself.

Any zealous young dinosaur admirer will enjoy the five-foot foldout, beginning readers the more because along the margin are identified some 75 fossil forms: reptile, fish, bird, plant, even one little mammal covert beneath a bush, waiting without realizing it for the crash of the comet. Any enthusiast who draws or paints such creatures of the past will read with empathy the recollections of the artist himself, who looks back to the happy and urgent years of his long, hard work. Those who can read very well will find much interesting information about the reconstruction of past life, written by two Yale paleontologists. A new recognition of flowering plants has changed our view of the Cretaceous since the 1940s, more perhaps than even the new evidence for hungry, gregarious, warm-blooded dinos.

Mature readers will be drawn to Professor Scully's brilliant account of the origin of this mural style and its technique, which were set forth in a treatise written around A.D. 1400 by the Tuscan painter Cennino Cennini. Scully's surprising case is solidly documented: by the 1930s that very book "in a development hard to credit...had become the bible of the Yale School of the Fine Arts." A reader is inclined to accept his judgment that by its mode of growth the mural appears as "slow and solemn" in movement as the dinosaurs were then thought to be. For old Cennini, too, "theory is the most worthy," for the artist must present "to plain sight what does not actually exist."

STATEMENT OF OWNERSHIP, MANAGEMENT AND CIRCULATION (required by 39 U.S.C. 3685). *1A.* Title of publication: Scientific American. *1B.* Publication number: 00368733. *2.* Date of filing: September 24, 1991. *3.* Frequency of issue: monthly. *3A.* Number of issues published annually: 12. *3B.* Annual subscription price: U.S. and its possessions, 1 year $36, all other countries, 1 year $47. *4.* Complete mailing address of known office of publication: 415 Madison Avenue, New York, NY 10017. *5.* Complete mailing address of the headquarters of general business offices of the publisher: 415 Madison Avenue, New York, NY 10017. *6.* Full names and complete mailing address of publisher, editor and managing editor: Publisher, John J. Moeling, Jr., 415 Madison Avenue, New York, NY 10017. Editor, Jonathan Piel, 415 Madison Avenue, New York, NY 10017. Managing Editor, Michelle Press, 415 Madison Avenue, New York, NY 10017. *7.* Owner: Scientific American, Inc., 415 Madison Avenue, New York, NY 10017; Holtzbrinck Publishing Holdings Limited Partnership, 415 Madison Avenue, New York, NY 10017; Handelsblatt GmbH, Kasernenstrasse 67, Postfach 1102, 4000 Düsseldorf, Federal Republic of Germany. *8.* Known bondholders, mortgagees and other security holders owning or holding 1 percent or more of total amount of bonds, mortgages or other securities: none. *9.* For completion by nonprofit organizations authorized to mail at special rates (DMM Section 424.12 only). The purpose, function and nonprofit status of this organization and the exempt status for federal income tax purposes: not applicable to this organization. *10.* Extent and nature of circulation: *A.* Total number of copies (net press run): average number of copies each issue during preceding 12 months, 830,790; actual number of copies of single issue published nearest to filing date, 921,000. *B.* Paid and/or requested circulation: *1.* Sales through dealers and carriers, street vendors and counter sales: average number of copies each issue during preceding 12 months, 129,202, actual number of copies of single issue published nearest to filing date, 211,515. *2.* Mail subscription (paid and/or requested): average number of copies each issue during preceding 12 months, 497,715; actual number of copies of single issue published nearest to filing date, 513,149. *C.* Total paid and/or requested circulation (sum of *10B1* and *10B2*): average number of copies each issue during preceding 12 months, 626,917; actual number of copies of single issue published nearest to filing date, 724,664. *D.* Free distribution by mail, carrier or other means of samples, complimentary and other free copies: average number of copies each issue during preceding 12 months, 18,133; actual number of copies of single issue published nearest to filing date, 28,701. *E.* Total distribution (sum of *C* and *D*): average number of copies each issue during preceding 12 months, 645,050; actual number of copies of single issue published nearest to filing date, 753,365. *F.* Copies not distributed: *1.* Office use, left over, unaccounted, spoiled after printing: average number of copies each issue during preceding 12 months, 21,187; actual number of copies of single issue published nearest to filing date, 9,780. *2.* Return from news agents: average number of copies each issue during preceding 12 months, 164,553; actual number of copies of single issue published nearest to filing date, 157,855. *G.* Total (sum of *E, F1* and *2*—should equal net press run shown in *A*): average number of copies each issue during preceding 12 months, 830,790; actual number of copies of single issue published nearest to filing date, 921,000. *11.* I certify that the statements made by me above are correct and complete. (Signed) John J. Moeling, Jr., Publisher.

ANNUAL INDEX 1991

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Science Press Sp. zoo
00 789 Warszawa, ul. Sloneczna 35, Poland

Advertising correspondence all editions:
SCIENTIFIC AMERICAN, Inc.
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Telephone: (212) 754-0550 Telex: 236115

ESSAY: MARX WASN'T ALL WRONG by Nathan Rosenberg

Perhaps we should hesitate before consigning Marx to the dustbin of history. Recent events in the Soviet Union are being interpreted as evidence of the final breakdown of Marxism, but one might question such a reading. What is, instead, absolutely evident is that centrally directed economies have proved incapable of delivering high standards of material well-being to the socialist masses.

Marx's writings essentially analyze the historical process by which capitalist societies grow and become transformed. Marx needs to be disengaged from the disastrous 20th-century economic experiments with socialism because in his view of history socialism would emerge only out of advanced capitalist societies. Socialism would arise after capitalist societies became wracked by their "internal contradictions." Socialist societies were destined, according to Marx, not only to resolve the internal contradictions of capitalism but to inherit the immense productive apparatus that mature capitalist societies were incapable of utilizing. When socialism finally appeared on the world stage, it would immediately take possession of a highly productive industrial technology, and it would administer that technology far more capably than the social system that had generated the technology.

Thus, in at least one limited but essential respect, the collapse of socialist economies serves to prove that Marx was right, not that he was wrong. Marx never argued that socialism, whatever the exact form it might take, would provide the institutions and the incentives needed to generate rapid technological change. Indeed, his point was precisely that when socialism emerged in the historical sequence that he predicted, those institutions and incentives would no longer be necessary. Socialism would succeed as a form of economic organization precisely because the problem of scarcity would already have been solved by the capitalist society that preceded it.

Marx was also right in his analysis of capitalism as a unique system that provided powerful impulses for initiating technological change. With the easy wisdom of retrospect, it is now apparent how difficult it is to provide effective substitutes for the technological dynamism generated by capitalist institutions. It has been 20th-century Marxists—not Marx—who developed the opportunist argument that it is possible to bypass the stage of capitalism and still develop a socialist society that has the productive capability to bring high standards of material well-being to the downtrodden proletariat. In this interpretation Gorbachev's program of *perestroika* is an explicit admission of the error in these drastically revisionist views. (As the cruel joke in the Soviet Union goes: "What is Communism?" Answer: "The most painful of all possible roads from capitalism to capitalism.")

For Marx, the historical accomplishments of capitalism resulted from its unique ability to generate and utilize technological change. As Marx and Engels point out in the *Communist Manifesto:* "The bourgeoisie has ... been the first to show what man's activity can bring about. It has accomplished wonders far surpassing Egyptian pyramids, Roman aqueducts and Gothic cathedrals.... The bourgeoisie cannot exist without constantly revolutionizing the instruments of production."

The competitive process also creates high rates of investment that lead to the rapid diffusion of new technologies. Marx understood clearly that growth in productivity is achieved not by mere inventiveness but by pressures to maintain the high rates of investment that lead to the rapid diffusion of technologies. Thus, companies as well as economies that are very innovative but incapable of achieving high investment levels are destined to lose out.

Of course, Marx argues that competitive capitalism inevitably gives way to the dominance of large-scale enterprise and, eventually, to monopolistic power. Perhaps he did not sufficiently appreciate the extent to which the search for new technologies is pervaded by extreme uncertainties that play a major role in determining the specific forms of institutional development in a maturing capitalist society.

Marx recognized these uncertainties, although only begrudgingly in the third volume of *Das Kapital,* published after his death and long after the immensely influential first volume. In the third volume Marx called attention to "the far greater cost of operating an establishment based on a new invention as compared to later establishments arising *ex suis ossibus.* This is so very true that the trail-blazers generally go bankrupt, and only those who later buy the buildings, machinery, etc., at a cheaper price, make money out of it."

This passage reveals that Marx explicitly recognized the extreme vulnerability of capitalists in their social role as carriers of technological innovation, the main source of capitalist dynamics. Had he paid more attention to this vulnerability in his earlier work, it would have been necessary to portray capitalists in a distinctly different light. It would also have been necessary to face up more candidly to the painful trade-offs that all societies must confront between greater equity and greater efficiency. But such an examination would have highlighted the weakness of capitalists, whereas Marx was intent on portraying their social power and their capacity for exploiting others. Marx may be said to have finessed the "equity versus efficiency" trade-off by assigning to capitalism the historical role of providing efficiency and to a later socialism the role of delivering equity.

Another powerful element of Marx's analysis continues to merit serious attention. Marx argued that science itself was an activity arising out of the needs of the productive process. Whereas economists before and since Marx have been inclined to treat science as an activity with economic consequences but not explicit economic antecedents or determinants, Marx's view was very different. He saw modern science as something that arose out of the incentive structure of capitalism. And, perhaps equally important, it was the special incentives of the capitalist marketplace that led to the large-scale application of scientific knowledge to industry. This last point is one that has been neglected at a very high cost by 20th-century socialist societies. The U.S.S.R., in particular, has first-rate scientific research in many disciplines but has been notoriously unsuccessful in linking these capabilities to the needs of industry and, especially, of agriculture.

Much in Marx on the subjects of science and technology can still be read with great benefit, and perhaps even profit. It would be unfortunate if the Marxist baby were to be thrown out with the socialist bathwater.

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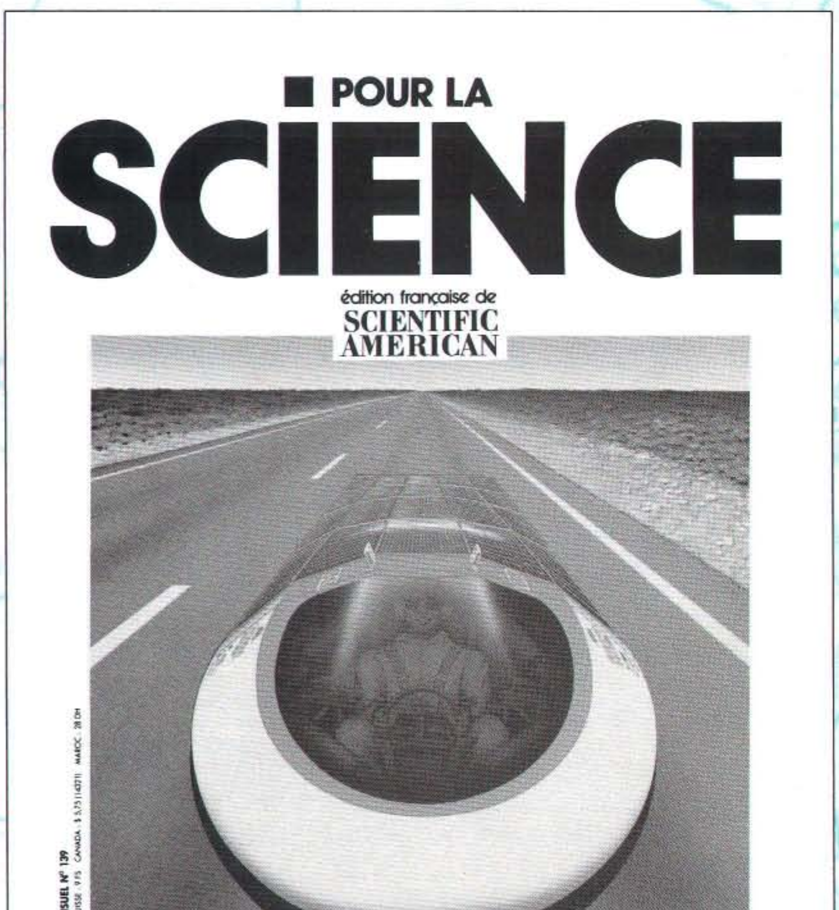

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